Influence of Spatial Abilities on Primary and Secondary Space Telerobotics Operator Performance

by

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ABSTRACT

Teleoperated manipulators have been invaluable tools during space missions. Arm operators work in pairs, with the primary operator controlling the arm and the secondary operator assisting by monitoring arm clearance and helping to avoid singularities. Individual ability to manipulate the arm and integrate camera views is believed to correlate with 3 subcomponents of spatial intelligence: spatial visualization (SV), mental rotation (MR) and perspective taking (PT). In particular, PT (the ability to imagine an object from another viewpoint) is thought to be important for integrating camera views.

Two experiments were performed; one on primary operator performance, and one on secondary operator performance. In Experiment 1, 19 naïve subjects were trained to manipulate a 6 degree of freedom (DOF) simulated arm using a pair of hand-controllers. Over 18 trials, the disparity between the arm's control frame and the cameras was varied between low (< 90 degrees) and high (> 90 degrees) conditions. We used the Cube Comparisons (CC) test to assess SV, the Vandenberg Mental Rotations Test (MRT) to assess MR, and the Purdue Spatial Visualization of Views Test (PSVT) and a Perspective Taking Ability (PTA) test to assess PT. Subjects with high PSVT scores moved the arm more directly to the target and were better at maintaining the required clearance between the arm and obstacles, even without a direct camera view. The subjects' performance degraded under the high disparity condition.

In Experiment 2, 11 naïve and 9 returning subjects were trained to manipulate the same simulated arm during 6 trials and then acted as a secondary operator observing an additional 32 trials. The MRT, PSVT, and PTA were used to assess spatial abilities. Though the primary operator task was slightly different, we confirmed many results of Experiment 1. Subjects with high PTA scores took less time, moved the arm more directly to the target, and moved the arm more fluidly, especially under the high disparity condition. High scorers on the PSVT and PTA were better at maintaining required clearance. Low PTA scorers looked from monitor to map more often. Prior experience with the arm didn't significantly improve task performance, and performance as primary operator didn't reliably predict performance as a secondary operator. However, subjects with high PSVT scores had better overall secondary operator performance and high PTA scorers were better at detecting problems before they occurred. The results of these studies could be used to customize initial training for astronauts. This research is supported by NSBRI through NASA Cooperative Agreement NCC 9-58.

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AD ASTRA PER ASPERA, SEMPER EXPLORO

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1 Introduction

On November 13, 1981, the Space Shuttle Columbia launched on its second flight with a new tool: the Payload Deployment and Retrieval System (PDRS)[1]. In the nearly 3 decades since, the PDRS has proven itself to be an invaluable tool, a critical component for deploying satellites and instrument packages, servicing the Hubble Space Telescope, and constructing the International Space Station (ISS). The ISS received its own arm, the Space Station Remote Manipulator System (SSRMS)[2], in 2001. [1]

Figure 1.1 - The SSRMS (left) is controlled via a Robotic Workstation (right)

Learning to manipulate either the PDRS or SSRMS requires many hours of training and practice. On the Shuttle, two windows and six cameras provide astronauts with views of their task. On the Space Station, there are no windows near the Robotic Workstation (RWS) in the Destiny Laboratory module; arm operators must depend on three monitors to provide camera views of their workspace. Manipulating the arm is relatively intuitive if the cameras are oriented in the same way as the arm's control frame (i.e., if the operator moves the arm to the left, the arm appears to move to the left in the camera view), but when the orientations of the cameras and the control frame do not coincide, the required mental transformations make controlling the arm a more complex and demanding task. The amount of training time required to control the arm safely and efficiently under conditions of high camera- vs. control-frame disparity varies significantly among astronauts.[3] This thesis focuses on the degree to which individual differences in spatial intelligence and/or bimanual control ability may underlie this phenomenon.

[1] The PDRS is also known as the Canadarm or Shuttle Remote Manipulator System (SRMS).

[2] The SSRMS is also known as the Candarm2.

[3] C.M. Oman, et al, "Advanced Displays for Efficient Training and Operation of Robotic Systems", NSBRI RFA-07001-S2

Operators of the robotic arm on the Shuttle or Space Station must constantly be aware of the spatial location and motion of all of the components in their workspace. This includes not only the arm but payloads, structures, and EVA astronauts. Maintaining this awareness and mentally integrating the information provided by each camera view are demanding tasks. Therefore operators most often work in pairs. The primary operator is responsible for actually manipulating the arm using the hand controllers while the secondary operator observes the task and assists with camera or mode adjustments, clearance and singularity monitoring, and task planning. Primary and Secondary operators both receive the same basic levels of training in order to become certified as an operator. Once they are selected for a mission, they are assigned specific roles.

The experiments described in this thesis were designed to give a better understanding of how an operator's inherent spatial and bimanual control abilities affect performance. With this information, training time could potentially be optimized by customizing a training program to each student's set of skills. The experiments covered basic training tasks given to astronaut candidates during early lessons of the Generic Robotics Training (GRT), as well as examples of tasks that students could encounter during training as a secondary operator.

2 Background

2.1 Space Telerobotics Operations and Training[4]

The PDRS and the SSRMS are used for on-orbit deployment and maintenance of satellites, like the Hubble Space Telescope; to build large space structures, like the ISS; and to inspect the Shuttle's thermal shield after launch and before re-entry. The PDRS and SSRMS are very similar; the main difference is that the PDRS has 6 Degrees of Freedom (DOF) and the SSRMS has 7 DOF. They are both controlled using a Robotic Workstation (RWS, Figure 2.1) [2].

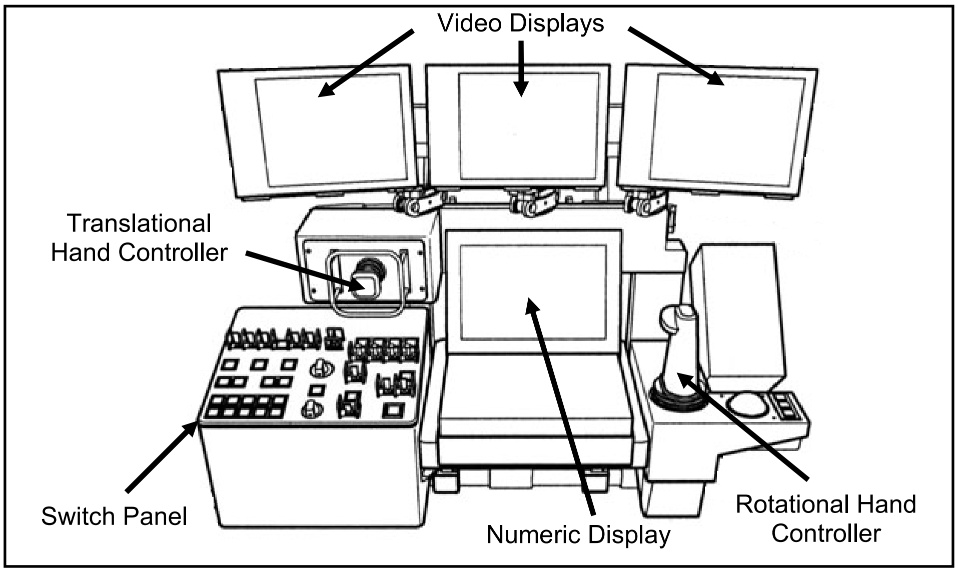

Figure 2.1 - ISS Robotic Workstation Components

The Space Shuttle's aft flight deck windows permit direct visual monitoring of robotic operations, but direct visual monitoring of the SSRMS is currently not possible.[5] The RWS' video monitors show views from cameras located around the Shuttle payload bay or on the ISS' structure. Astronauts can select and pan/tilt/zoom appropriate cameras to obtain the best possible view, as well as multiplex more than one view on a single screen, though this sacrifices image size and field of view. Unfortunately the cameras cannot be rolled, so depending on the orientation of the camera mount, the scene may appear tilted or even upside down. Visual feedback provided by the cameras is usually the only source of dependable information about the arm's motion and clearances. Supplementary but less accurate information on the end-effector's position and orientation is provided by a numeric display. The arm's operator can specify that the hand

[4] This section is adapted from the 2007 research proposal "Advanced Displays for Efficient Training and Operation of Robotic Systems", C.M. Oman, et al, NSBRI RFA-07001-S2, with the authors' permission.

[5] If the Cupola is installed, it will house another RWS and give direct views during some robotic operations, such as docking the Japanese H-II Transfer Vehicle (HTV).

controllers' command frame be aligned with a frame fixed to the spacecraft (known as external control mode) or fixed to the tip of the end-effector or its payload (internal control mode.) A typical operation starts with a “Fly-To” phase where the arm is moved near the payload, continues with an “Alignment” phase where the end-effector is aligned with a grapple pin on the payload, and finishes with the “Grapple” phase, where the end-effector is locked onto a grapple pin on the payload. Once the payload is grappled and locked to the arm, the process is repeated as the payload is moved to its desired position.

Astronauts work in pairs to operate the PDRS or SSRMS. The primary operator (known as the M1 on Station) is in charge of manipulating the arm with the hand controllers while the secondary operator (known as the M2) is in charge of tracking moving objects with the cameras, switching camera views as instructed by the M1, monitoring obstacle clearance, avoiding arm mechanical singularities and maintaining overall situational awareness.[6] A secondary operator is expected to monitor the arm's motion and position, as well as the position of the target and any other objects in the workspace. Both operators receive the same basic training and those with the best performance are classified as M1s and those with lower but acceptable skills are classified as M2s. Usually, operators are assigned their flight position based on their post-training classification, but when necessary, an astronaut designated as an M2 after training can be given the M1 flight position for specific tasks. In off-nominal situations, however, the better qualified operator will usually take over as the M1. Crewmembers are almost always certified to fill either position, and the mission designation depends on their other assignments.[7]

Once selected, astronauts begin their teleoperation training with the 15-lesson Generic Robotics Training (GRT), where they are taught basic manipulation tasks (e.g. flying the arm, grappling objects) and strategies for choosing appropriate camera views. Two training systems are used throughout the GRT: the Basic Operational Robotics Instructional System (BORIS) and the Multi-Use Remote Manipulator Development Facility (MRMDF). BORIS is a desktop virtual 6 DOF system simulating the PDRS; the MRMDF's physical 7 DOF system simulates the SSRMS.

During robotics training, astronauts are evaluated after specific lessons by a group of Robotics Instructors and Instructor Astronauts[8]. Performance scores are based on a sum of 9

[6] The primary operator is known as the R1 on the Shuttle and the secondary operator is known as the R2.
[7] L. Snider, Robotics Trainer, NASA Johnson Space Center, personal communication.
[8] Instructor astronauts are not involved in all the evaluations, generally just in the final stage.

standardized criteria, weighted by their estimated impact on mission success. Higher weights are given to criteria relating to spatial/visual perception, situational awareness, clearance monitoring, camera selection and real time tracking, motion smoothness, and the ability to maneuver along more than one axis at a time. Astronauts who received higher scores on the training evaluations are assigned to M1 positions, although it is the M2's main task to monitor for arm clearance and singularities and provide overall situational awareness support. Astronauts who do not earn the minimum required grades undergo remedial training, which typically focuses on visualizing the orientation of the control reference frame from the camera frame. The training methods strongly suggest that spatial ability plays an important role in space teleoperation performance. Being able to predict a trainee's spatial weaknesses and strengths could allow the training process to be customized and therefore more efficient.

2.2 Spatial Ability

Spatial abilities (SpA) determine how we imagine, transform, and remember visual information, and are an important component of general intelligence. It is believed that spatial abilities depend on such factors as age, gender, and personal experience. Over the past 40 years, different subcomponents of spatial ability have been identified. The psychometric method assumes that SpA has many components and different authors classify them slightly differently. However, there are two main classes relevant to telerobotics – spatial visualization (SV) and spatial orientation (SO).

Spatial Visualization

SV is a person's ability to visualize the transformation of objects or surfaces in an image into other configurations, such as unfolding a sheet of paper. The Kit of Factor-Referenced Cognitive Tests [3] contains several paper-and-pencil tests for testing spatial visualization abilities, including the Cube Comparisons (CC) test. In the past, CC was classified as a way of measuring a subset of SO, but it is now classified as a measure of SV ([4] - [6]).

During the test, subjects are shown twenty-one pairs of cubes (two examples are shown in Figure 2.2) with a letter or shape on each face. They must decide if the cubes are different from each other or if they are two rotated views of the same cube. The test is given in two three-minute sessions and measures the subject's ability to rotate an object mentally.

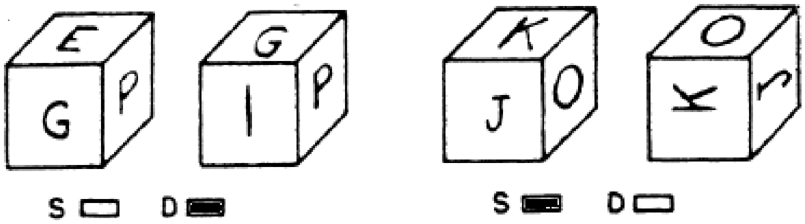

Figure 2.2 - Examples from the Cube Comparisons Test

Spatial Orientation

SO is a person's ability to imagine different views of an object and is subdivided into perspective taking (PT) and mental rotation (MR). The main difference between these processes is the frame of reference that is manipulated to get the new viewpoint. With MR, it is the object that is imagined to be rotating while the observer remains fixed; with PT, it is the observer that is imagined to be moving around the object. PT and MR can be distinguished experimentally, though, according to Kozhevnikov and Hegarty [7] and Hegarty and Waller [8], individuals with strong PT skills also tend to have good MR scores. On average, males slightly outperform females on both tests.

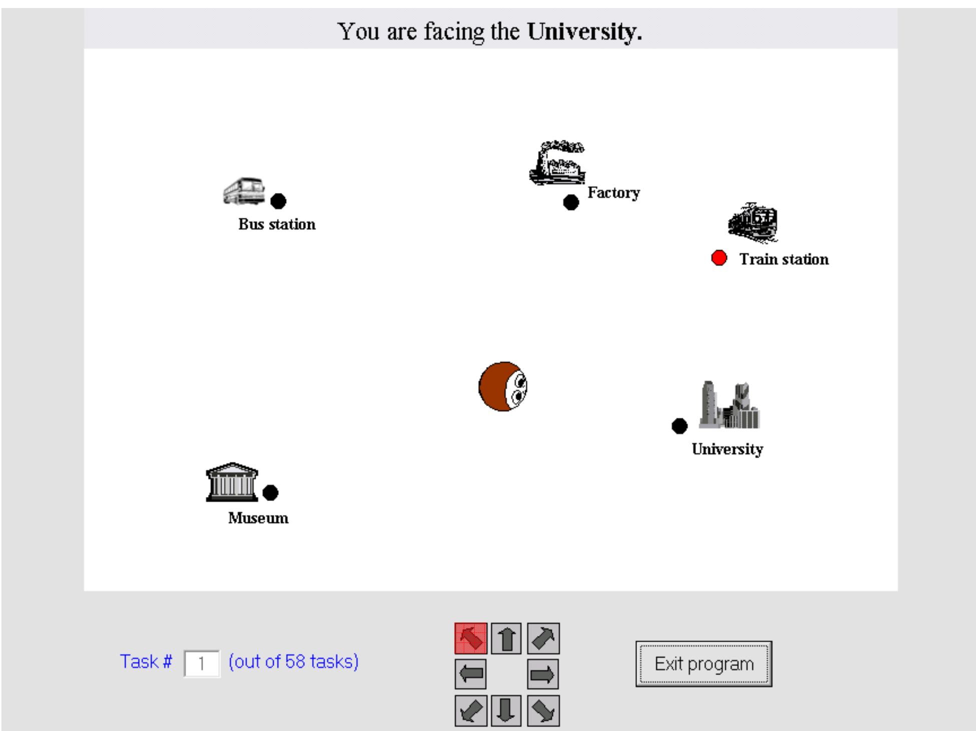

Figure 2.3 - Screenshot from the Perspective Taking Ability (PTA) Test

In the computerized Kozhevnikov Perspective Taking Ability (PTA) Test (Figure 2.3, [9]), the subject is shown a top-down (plan) view of a person surrounded by several locations within a town. The subject is instructed to imagine being oriented like the person in the picture. After 5 seconds is allowed for study of the environment, a flashing red dot appears beside one of the elements. The subject must then indicate the direction of this element relative to the person's orientation. There are 58 trials and the subject's score is determined from angular error and response time. In the example in Figure 2.3, the subject would imagine themselves facing the University and respond that the Train Station is in the indicated direction (45° to the left from forward). Kozhevnikov et al [9] found that either PT or MR strategies can be used for this test. The chosen strategy depends on the angle between the egocentric frame and the imagined heading: mental rotation is often used for small angles (< 90°), and perspective taking is used for larger angles, except for 180°.

Research by Tversky and others ([10] - [13]) has shown that when performing a PT task based on pictures, maps, or text descriptions of an environment, the body axes of the observer and the direction of gravity determine the reference directions. If the observer's reference frame does not match that of the environment (such as if the observer is upside-down or is rotated more than 90° with respect to the environment frame), left-right and front-back errors appear. Disparities commonly occur in teleoperation when the orientation frame of the observer (the camera-frame) does not match the reference frame for the arm's movements (the control-frame.) Additionally, response times are longer when the imaginary viewpoint is within the array of imagined objects than when the viewpoint is outside looking in. This is because when some objects within an array are behind you, larger mental rotation angles are needed to visualize them. Camera views showing both "within" and "outside" perspectives are used in teleoperation.

In the Purdue Spatial Visualization Test: Visualization of Views (PSVT, [14]), the subject is shown isometric views of various solid objects in the middle of a see-through cube. For each of the 30 trials, a black dot is located on one of the cube's vertices and the subject must determine which of the five answer options represents the view of the object as seen from that location (example in Figure 2.4. The answer E represents the view of the object from the indicated corner of the see-through cube). The subject completes as many of the trials as possible within 6 minutes. Although the PSVT has not been formally validated as a PT test, the majority of subjects in previous Man-Vehicle Laboratory (MVL) experiments self-reported that they used PT more than any other strategy. Telerobotics performance may correlate differently with PSVT scores from the way it correlates to scores on a 2-D test like the PTA.

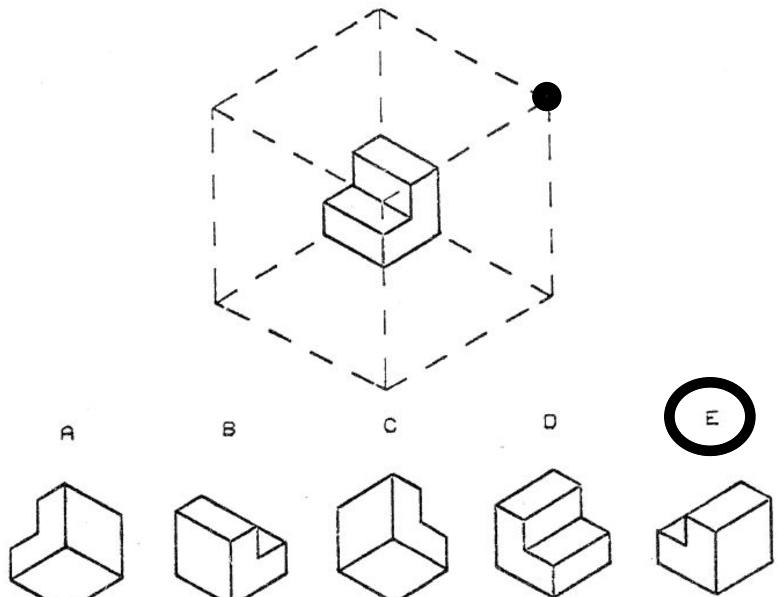

Figure 2.4 - Example from the Purdue Spatial Visualization Test (PSVT)

In the Vandenberg Mental Rotations Test (MRT), a classic test of MR ability, the subject is shown a picture of a 3-dimensional object made of multiple cubes (example in Figure 2.4). For each of two sets of ten trials, subjects must identify the two of four options are pictures of the same object rotated into different orientations. Subjects complete as much of the set as possible in 3 minutes before moving on to the next set. Previous Man-Vehicle Laboratory (MVL) telerobotics studies used the Card Rotations (CR) test to assess MR ability. Since CR is now considered a test of SV ability, we chose the MRT instead, a more specific test of MR ability, for the present studies. It was hypothesized that PT and SV were most important for telerobotics, although there is believed to be a strong association between MR and SV.

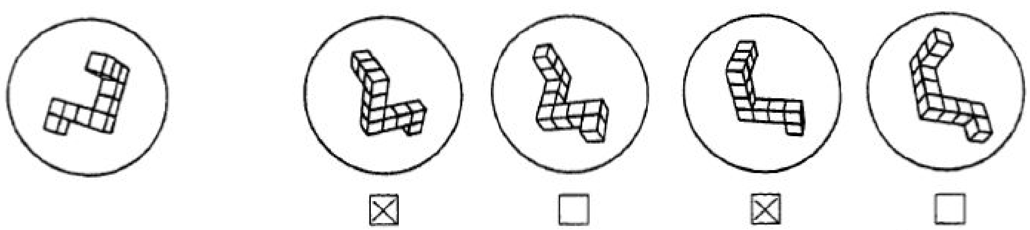

Figure 2.5 - Example from the Mental Rotations Test (MRT)

2.3 Bimanual Control Ability

While spatial abilities contribute importantly to teleoperation performance, motor control is also critical. Previous MVL telerobotics studies have not assessed bimanual control ability. During GRT training, students are encouraged to perform translational movements along or rotational movements about multiple axes simultaneously to increase efficiency. However, Bock et al. [15] found that their subjects were slower and less accurate when they had to coordinate the movements of two single-axis joysticks instead of using only one dual-axis joystick to drive translational movements. The mental demands imposed by these bimanual movements decreased with practice.

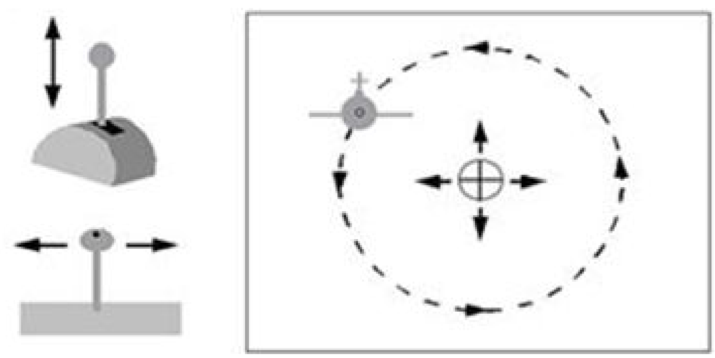

Figure 2.6 - Air Force Two-Handed Coordination Test

The military has used Two-Handed Coordination Tests (THCT, Figure 2.6, [16]) for pilot selection for many years. In those, the participant must use two single-axis joysticks to keep crosshairs centered over an airplane moving at a varying rate around an ellipse. The score is determined from the error in the horizontal and vertical directions. [17]

Figure 2.7 - Screen shots from the MVL Bimanual Control (BMC) Exercise

For our experiments, we developed a “MVL Bimanual Control” (BMC) exercise, which was modeled after NASA GRT tracing tasks. Subjects used both translational and rotational movements to trace a path around an image of the Shuttle's nosecone (white oval, shown in Figure 2.7), keeping one line of the end effector camera crosshairs tangent to the edge. Scores were taken from the last 3 of 4 repetitions and were based on completion time, angle error, and percentage of time spent with both controllers deflected simultaneously. The test has not been formally validated, but since the test has face validity, scores on it were believed to give a general indication of the subjects' manual control ability.

2.4 Signal Detection Theory

Evaluation of a secondary telerobotics operator's overall ability to correctly detect problems that arise during operations can be approached using techniques adapted from signal detection theory (SDT) [18]. An SDT based analysis of primary teleoperator performance was previously employed by Liu et al [19] in a retrospective evaluation of NASA astronaut training performance. From the SDT perspective, two discrete states exist during teleoperation: the presence ("signal") or absence of a potentially dangerous condition. Due to noise in the detection system (e.g., poor video images that cannot easily be interpreted), the secondary telerobotics operator cannot perfectly determine whether the signal condition or a safe (“noise”) condition is present. The operator hopes to detect all of the cases in which a signal is present, but, in practice, misses some or responds in error as though to a signal when there is none. The possible combinations and responses are shown in Figure 2.8.

State of the World

		Signal	Noise
Response	Yes	CORRECT DETECTION	FALSE ALARM
	No	MISSED DETECTION	CORRECT REJECTION

Figure 2.8 - Four Outcomes of Signal Detection Theory

According to Green and Swets [18], the SDT model assumes two stages for information processing when detecting a signal: first, sensory evidence is collected about the presence of the signal, and then a decision is made as to whether the evidence indicates a signal or the absence of one. The external stimuli create neural activity in the brain. Normally there will be more neural evidence (X) when a signal is present than when it is absent. When there is enough neural evidence to indicate the signal condition, X rises above a threshold level (X_c) and the operator will respond "yes." Accordingly, if there is not enough neural evidence, the operator will respond "no." Since the signal usually doesn't contain a large amount of information, X is usually not much greater when signals are present than when they are not. Random fluctuations in the environment and neural "noise" cause X to change continuously without any change in the signal. Therefore, X_c may be exceeded in the absence of a signal (false alarm), or it may not be met even when there is a signal present (miss).

The level of neural evidence that the operator adopts as a decision threshold will depend on the value attached to a correct detection and the cost of a false alarm. That is, operator behavior in signal detection tasks can be manipulated by changing the perceived costs and benefits. For example, if it is highly desirably that no signal ever be missed, the operator could be given large rewards for hits and assessed large penalties for misses. If, instead, it were more important to avoid false alarms, the operator could receive large penalties for them. Experiments by Green and Swets showed that operators were overly cautious if penalties were very low and prone to risk if penalties were very high. [20] Overall performance can be characterized by calculating the probability of a hit, P(H), (or correct detection) vs. the probability of a false alarm, P(FA).

Green and Swets showed that operator performance follows a “Receiver Operating Characteristic” curve. Thus the ROC curve plots P(H) against P(FA) for various values of operator threshold, which in turn depends on the “payoff”, the perceived costs of false alarms and benefits of correct detection. For the same operator and same observation conditions, changing payoff will result in a change in the operating point on the ROC curve. If false alarms are highly penalized operators tend to operate on the left side of the ROC curve, accepting lower P(H) in order to minimize P(FA). If false alarms are acceptable or missed detections are heavily penalized, operators will use a lower threshold and operate more to the right side of the ROC curve. Overall performance can be characterized by the total area under the ROC curve. If an operator has nearly perfect performance, the “knee” in the ROC curve is in the extreme upper left hand corner of the ROC plot and the area under the curve will be 1 (= 100%). [20]

2.5 *Previous Research*

2.5.1 External Studies

Studies of the effects of reference frames and the use of displays in telerobotics provide indirect evidence that performance may be correlated with spatial abilities.

- Spain and Holzhausen [21] found that performance in an undersea telerobotic task does not always improve when the number of available viewpoints increases. They concluded that subjects often did not use the extra information those additional viewpoints provided because that would have increased mental workload.
- DeJong et al [22] studied how disparities between the controller inputs, camera and display frames, and the end-effector can affect performance. They learned that performance improved as the number of frames with coincident orientations increased.
- Lamb and Owen [23] found that using an internal control mode for simulated SRMS teleoperation tasks resulted in higher performance than using an external control mode. In their study, subjects manipulated a robotic arm using a head-mounted display and two controllers in a virtual environment. They were required to fly toward a payload, grapple it, and maneuver it into the Shuttle's payload bay.

Other studies have found direct correlations between spatial abilities and teleoperation performance, but none studied the use of multiple displays:

- In the medical field, laparoscopic surgery is performed using teleoperation. Eyal and Tendick [24] saw a significant correlation between a subject's ability to learn good positioning of the laparoscope and their scores on SV, MR, and PT tests.
- Tracey and Lathan [25] saw lower completion times on a pick-and-place task for subjects with higher spatial abilities
- Lathan and Tracey [26] found that 2D navigation performance with a teleoperated robot correlated to high spatial ability scores.

2.5.2 MVL Telerobotics Research

The MIT Man-Vehicle Laboratory (MVL) conducted its first studies of the effect of spatial ability on space teleoperation performance in 2007. A first set of experiments [27] tested whether performance correlated with perspective taking (used to integrate camera information into an environmentally-referenced frame) and spatial visualization (used when visualizing the manipulation of the payload with respect to the robotic arm). Subjects used two hand controllers to manipulate a simulated 6 DOF arm while performing generic robotic pickup and docking tasks. The separation between the camera views' and the control frame was changed between the tasks (shown in Figure 2.9). PSVT and PTA were used to measure PT and CC was used to measure SV.

The study concluded that PTA scores predicted performance on pickup and docking subtasks; CC scores were related to performance measures that did not necessarily require PT, such as docking accuracy. Subjects with high PT scores had more efficient movements, but were not necessarily faster at the pickup subtask. They were, however, significantly faster and more accurate at the docking subtask. High SV scorers docked more accurately. Females were slower and had lower accuracy, in addition to having lower spatial ability scores. [27]

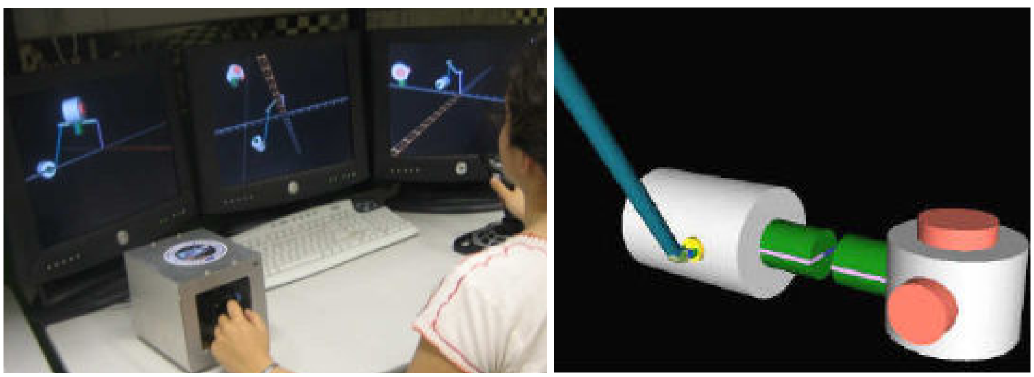

Figure 2.9 - Telerobotics Experiment Setup (left), Docking Task Example (right)

A second study conducted collaboratively with NASA Johnson Space Center (JSC) examined the effectiveness of spatial intelligence and NASA robotic aptitude tests in retrospectively predicting performance on a qualification test after robotics training. [19] Forty astronauts who had completed at least one training course (GRT, PDRS training, or SSRMS training) were given a set of tests including the MRT, PSVT, and PTA. Spatial ability scores predicted performance in Situation Awareness and Clearance tasks during GRT, but, because of the risk of misclassification, the results were only reliable enough for use in customizing training. It was suggested that the reliability of the predictions could be enhanced by improving the current relatively blunt scoring techniques used in the evaluation test.

3 Experiment 1

3.1 Objectives

The objectives of this experiment were:

1. To extend previous studies of teleoperation training and performance during Fly-To and Alignment phases with improved spatial testing, more trials, better performance metrics, and a more realistic training environment.
2. To investigate the effect of spatial and bimanual control abilities on performance
3. To investigate the effect of disparity between camera- and control-frame orientation on telerobotics performance
4. To identify spatial and bimanual control tests that could help NASA trainers predict performance in early training.

3.2 Hypotheses

We hypothesized that:

- Subjects with higher SV, SO, and BMC skills would perform tasks with a simulated robotic arm better[9] than those less skilled, regardless of disparity.
- Large (greater than 90°) disparities between the orientations of the camera- and control-frames would negatively affect performance, and subjects with higher SO and SV skills would perform better under large disparity conditions because those require MR and PT.
- Subjects with stronger SO, SV and BMC skills would perform better than their counterparts when using the internal control mode for the Fly-To segment and the external control mode for the Alignment segment.[10]

[9] Performance was defined by several metrics including time to complete a task, percentage of time spent moving, number of problems such as violation of clearance limits, error from the best path to the target, number and duration of continuous movements, and final distance from the target.

[10] During GRT training, students normally perform the Fly-To segment in external control mode and the Alignment segment in internal control mode. Successfully using the other frame for each of these segments requires more mental computations.

3.3 *Methods*

3.3.1 MVL DST Environment

We created a virtual simulation, the MVL Dynamic Skills Trainer (DST, shown in Figure 3.1), which was modeled after the Basic Operational Robotics Instructional System (BORIS) used by NASA in the astronaut Generic Robotics Training (GRT). The dimensions of the workspace were obtained from the NASA JSC Robotics Training Handbook [28]. The environment included a 6 DOF arm and a 15 m deep x 30 m across x 15 m high room with a workbench, target box, and overhead solar array. The simulation was constructed using AC3D v6.2, a 3-D modeling program (Inivis Limited, Ely, UK) and Vizard v3 VR Toolkit (WorldViz, Santa Barbara, CA).

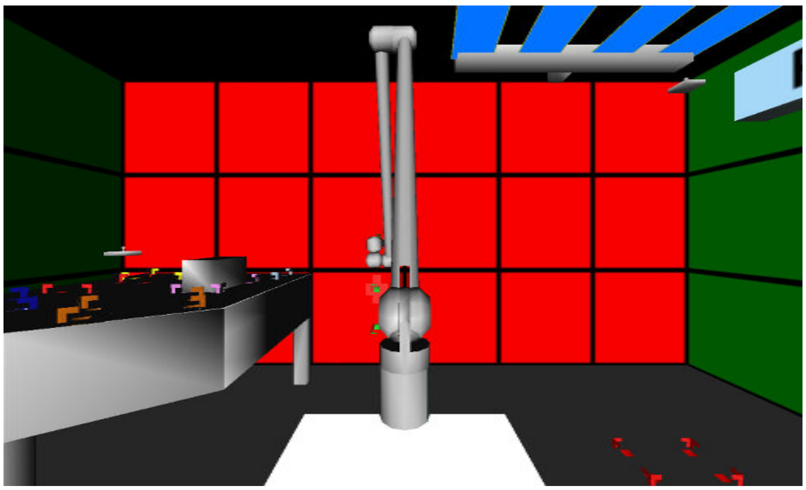

Figure 3.1 - MVL Dynamic Skills Trainer Virtual Environment

3.3.2 MVL DST Arm

The MVL DST robotic arm simulated the BORIS arm with the same length (14 m) and joints (Shoulder Yaw, Shoulder Pitch, Elbow Pitch, Wrist Pitch, Wrist Yaw, and Wrist Roll). The RRG Kinematix v.4 plug-in (Robotics Research Group, University of Texas) was used to calculate the inverse kinematics; Table 3.1 lists the arm's Denavit-Hartenberg (DH) conventions[11]. In order for the inverse kinematics to be calculated properly, the neutral position for the Wrist Yaw joint was set at +90°; this unintentionally created an extra singularity condition that the BORIS arm does not have.

[11] The base frame for the DH conventions was aligned with the Z-axis pointing downward, the X-axis pointing along the arm (when in the neutral or straight-out position), and the Y-axis pointing to the right.

Table 3.1 - MVL DST Arm Denavit-Hartenberg Parameters

Joint (i)	α(i-1)	a(i-1)	d(i)	θ(i)
1 = Shoulder Yaw	0°	0 mm	-1000 mm	Variable
2 = Shoulder Pitch	-90°	0 mm	0 mm	Variable
3 = Elbow Pitch	0°	6000 mm	-500 mm	Variable
4 = Wrist Pitch	0°	6000 mm	-500 mm	Variable
5 = Wrist Yaw	90°	0 mm	-500 mm	Variable
6 = Wrist Roll	-90°	0 mm	-1000 mm	Variable

The arm was controlled using two 3-axis joysticks: the translational hand controller (THC, Figure 3.2a) and the rotational hand controller (RHC, Figure 3.2b). The THC was custom-built using a CH Products Model 100 2-axis joystick, a linear potentiometer, and a 3-axis/4-button USB controller card; it could be moved up/down, right/left, and forward/backward. The use of the linear potentiometer made the forward/backward motion slightly different from that of NASA's THC. The RHC was a Logitech Extreme3DPro USB game controller with 3 axes (right/left, forward/backward, and twist). Unlike NASA's RHC, the point of rotation was at the base of the controller instead of in the hand-grip. The controllers had a central dead zone (created by the software) in all degrees of freedom (0.25 of the range in each direction). The data from the joysticks was captured at 100 Hz.

Figure 3.2 - MVL Translational (left) and Rotational (right) Hand Controllers

3.3.3 Task

Subjects were asked to maneuver the arm's end-effector from a constant start point to a target box; they had to determine the best route to “fly-to” the target as quickly as possible while maintaining proper clearance (0.6 m) from the walls and other obstacles and avoiding joint angle limits. Using a camera located on the end of the arm and other cameras set around the room, the subjects positioned the end-effector 1.5m above the top surface of the target box and then aligned it so that it was perpendicular to that surface (as shown in Figure 3.3). Figure 3.3

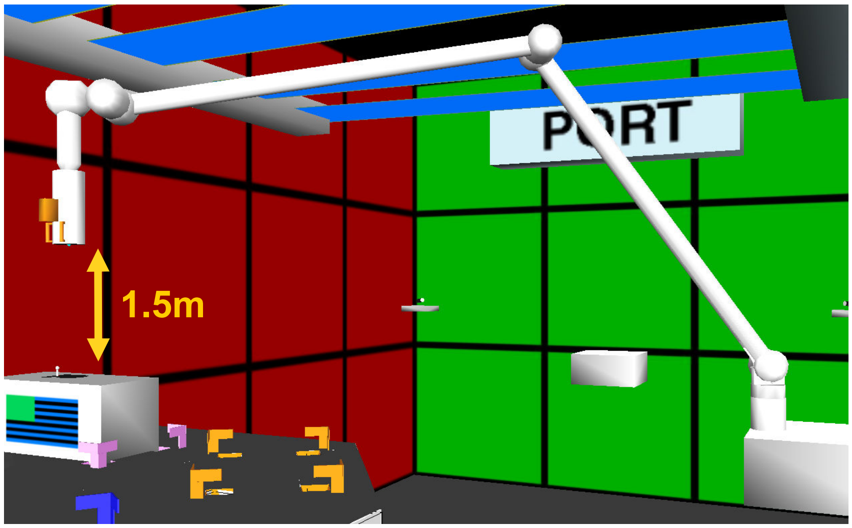

Figure 3.3 - Final Segment of Experiment 1 Task

The trials varied in the location of the target, the control mode used (Section 3.3.4), and the selected cameras (Section 3.3.5). There were 3 possible locations (berths) for the target box: 2 berths on the table and 1 on the aft wall. A support (not shown in the figure) was added to the target box so it would rest at an angle, which increased the difficulty of aligning the arm with the top surface. The inclination angle varied (yaw, pitch, or both) depending on the location of the target. The task design for this experiment combined two types of activities from GRT (fly-to and alignment) into a single task.

3.3.4 Control Modes

Subjects performed the tasks using either an external (exocentric) or an internal (egocentric) control mode. The type of control mode is characterized by the relative orientation of the command frame (inputs from the hand controllers) to the display and world reference frames. As shown in Figure 3.4, one alignment reference (Display Frame) was fixed with respect to the room and the other (Frame of Reference, FOR) was fixed with respect to the arm. The command frame was always located at the same point as the FOR, but it was oriented with the Display Frame in external mode and with the FOR in internal mode.

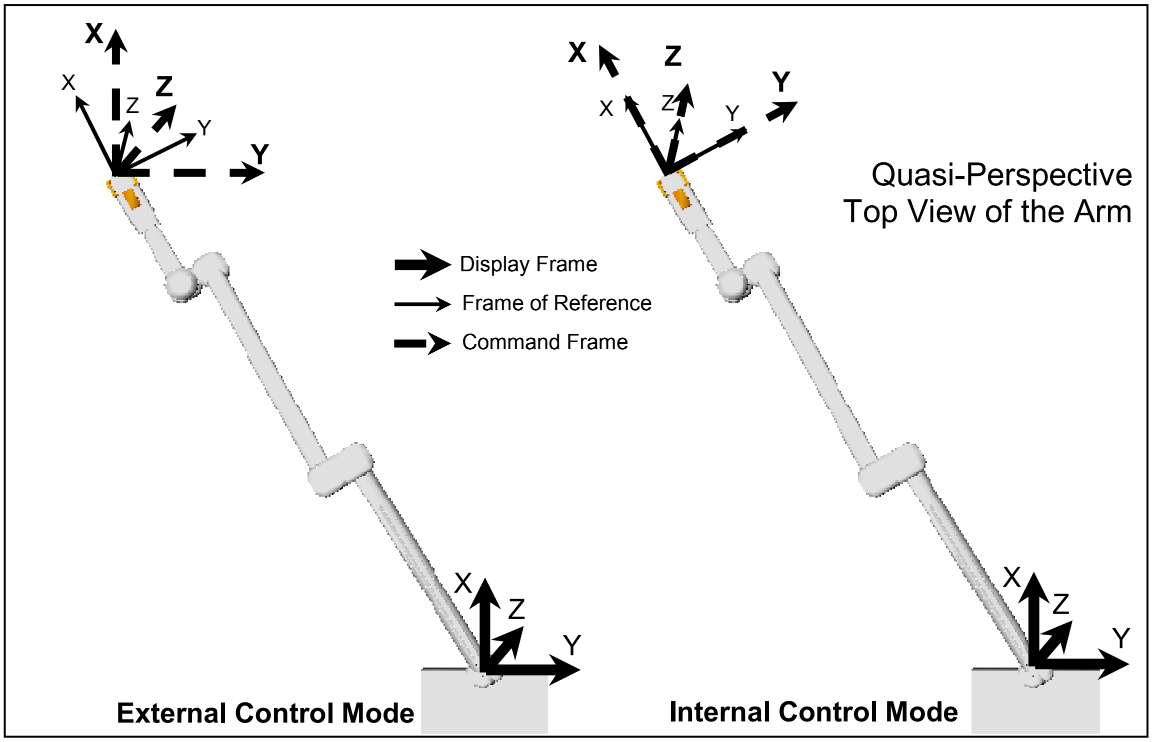

Figure 3.4 - Frame Orientations For External and Internal Control Modes

The trials were divided into the Fly-To (first) and Alignment (second) segments; the computer automatically ended the Fly-To segment when the arm came within 1.5 m of the goal position. The Alignment segment ended when the subject pressed a button on the keyboard to signify they had finished manipulating the arm.

3.3.5 Camera Configurations

The environment contained five cameras: one fixed camera at each corner of the room and one mobile camera mounted on the end-effector. The fixed cameras were positioned 6.25 to 8 m above the floor of the environment, with an elevation angle of zero degrees and an azimuth angle that varied from camera to camera.. The cameras positions allowed for the experiment to manipulate the disparity between the camera- and control-frames. Cameras 1 and 4 made up the low (less than 90°) disparity configuration and Cameras 2 and 3 made up the high (greater than 90° but not equal to 180°) disparity configuration. A 180º case was not presented, by design, since prior research showed that subjects use strategies other than PT.

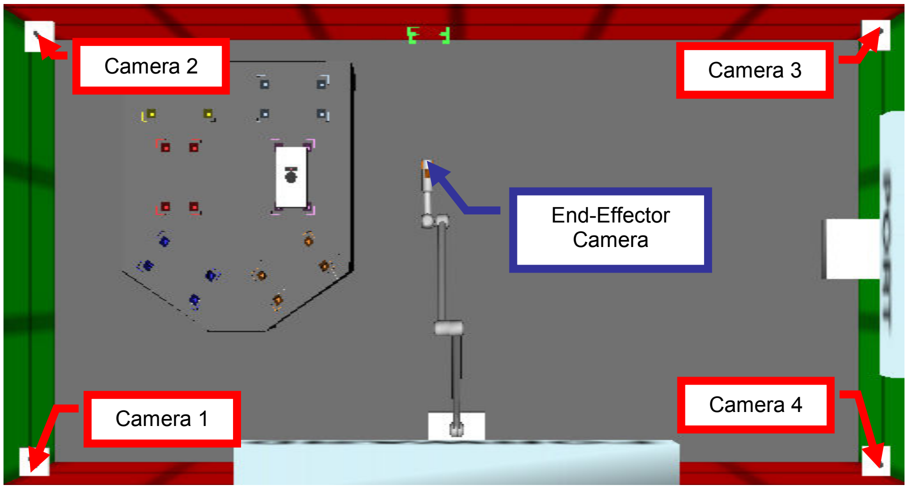

Figure 3.5 - MVL DST Environment Camera Locations

Three monitors provided subjects with their views of the environment. Figure 3.6 shows Camera 1 on the left and Camera 4 on the right. In the other camera configuration, the left-side monitor showed Camera 2 and the right-side monitor showed Camera 3. The end-effector camera was always shown on the center monitor. During NASA's Generic Robotics Training, students can adjust the camera orientation and zoom on each monitor as needed. In this experiment in the MVL DST, the camera configurations were kept fixed in order to allow comparison between the subjects. Since the cameras could not be panned or tilted in this experiment, the field of view for each camera was set greater than that usually used in the GRT.

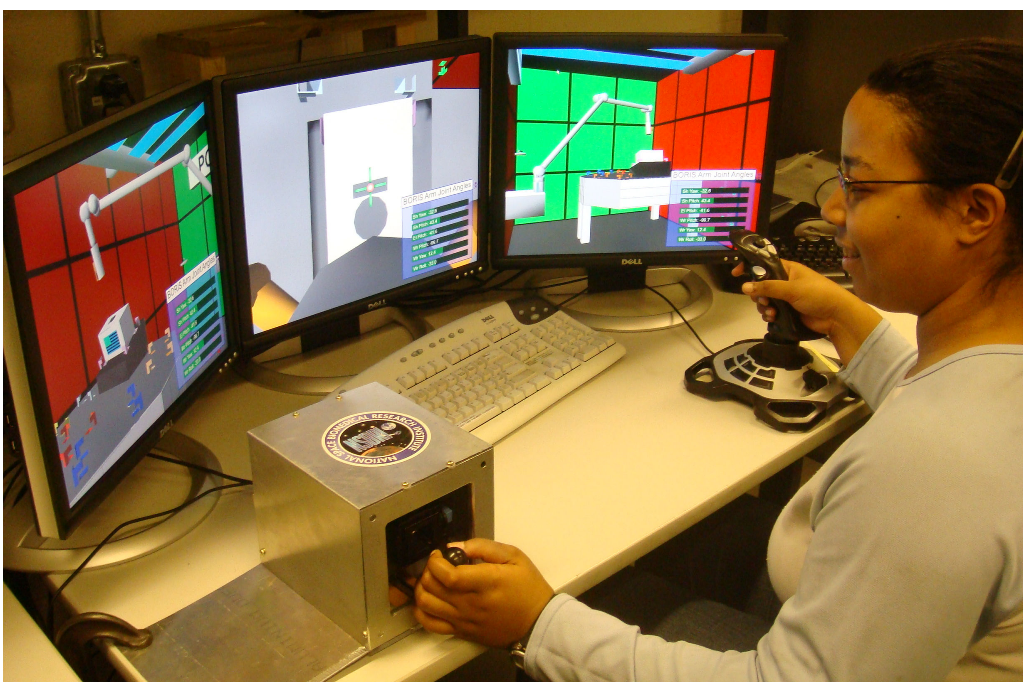

Figure 3.6 - Experiment 1 Setup with Three Monitors and Controllers

3.3.6 Performance Metrics

After each trial, variables characterizing the subject's performance were recorded in a Summary Data File. A summary of the metrics is presented in Table 3.2. The occurrence of operationally significant events during the trial (e.g. collisions, clearance violations, activation of Vernier movement rates, etc) was recorded in a Lesson Data File, whose metrics are presented in Table 3.3. Throughout each trial, the position of the end-effector, joint angles, and controller inputs were recorded at 100 Hz to a Joint Angle File in case any additional analyses were desired after the experiment was completed. The duration of each continuous movement was recorded to a Movement Data File and the arm's final position and orientation were recorded to an End Data File (this information was later integrated into the Summary Data File).

Table 3.2 - Summary Data File Measures of Performance

Measures	Description	Recorded	Calculated
Trial Time[12]	Total time (sec) that the subject took for the trial	X	
Movement Time[12]	Total amount of time (sec) the arm was moving	X	
AvgMovement[12]	Average duration (sec) of a continuous movement	X	
ContMoves[12]	Number of continuous (discrete) movements made	X	
TransMA Time[12]	Amount of time the arm was translating along 2+ axes	X	
RotMA Time[12]	Amount of time the arm was rotating about 2+ axes	X	
BiMan Time[12]	Amount of time the arm was both translating/rotating	X	
Moves[12]	Number of changes in direction that were made	X	
TMAMvs[12]	Total number of translational changes in direction that were made along 2+ axes	X	
RMAMvs[12]	Total number of rotational changes in direction that were made along 2+ axes	X	
BiMvs[12]	Total number of changes direction that were both translational and rotational at the same time	X	
AngL	Number of times that the subject was given a warning about being within 10° of a hardstop	X	
HStop	Number of times the subject reached a hardstop	X	
Singularity	Number of singularities that the subject reached	X	
Clearance	Number of times that a part of the arm was within 0.6m of another object or wall	X	
Collisions	Number of times that the arm hit another object or wall	X	
PathErr	Average squared distance (meters ^{2}) between the end-effector tip and the pre-defined shortest path from the start point to the target	X	

[12] For each of these measures, a "reset" measure also existed. The reset variables only recorded the amount of time or the number of movements from the final time the reset button was pressed until the end of the task. If the reset button was not pressed, the reset measure was the same as the actual measure.

Measures	Description	Recorded	Calculated
Resets	Number of times the subject pushed the reset button		X
Vernier	1-digit binary variable: Did the subject engage Vernier mode during the trial		X
Moving %	Percentage of time that the subject was moving the arm = Movement Time / Trial Time		X
Trans MA %	Percentage of moving time the arm was translating along 2+ axes = TransMA Time / Movement Time		X
Rot MA %	Percentage of moving time the arm was rotating about 2 + axes = RotMA Time / Movement Time		X
Bimanual %	Percentage of moving time the arm was translating and rotating = BiMan Time / Movement Time		X
Align X, Y, Z	Error along the X,Y, and Z axes between the end-effector's final position and the 1.5m target		X
Align D	Distance error between the end-effector's final position and the 1.5m target		X
Align P, Y, R	Error in pitch, yaw, and roll angles between the end-effector's final position and the 1.5m target		X

Table 3.3 - Lesson Data File Measures of Performance

Measures	Description
Time	Time at which the problem occurred
Collision Code	Eight-digit binary code that identified a collision or clearance violation, the part of the arm involved, and the part of the environment involved.
Singularity	1-digit binary variable for whether or not a singularity was occurring (1 =yes)
AngL	1-digit variable indicating a joint near a hardstop (1=Sh Yaw, 2=Sh Pitch, etc.)
HStop	1-digit variable indicating a joint had hit a hardstop (1=Sh Yaw, 2=Sh Pitch, etc.)
Vernier	1-digit binary variable indicating if Vernier rates were active
Reset	1-digit variable indicating the number of times the arm had been reset

3.3.7 Subjects

The experimental protocol was reviewed and approved by MIT's institutional experimental review board. A total of 23 subjects (7 females) were tested (demographics listed in Appendix A). Data from one male subject was discarded because he was unable to finish the second session. We also discarded the data for 3 other subjects (1 female) because they did not understand the instructions or performed with a cavalier attitude. The remaining subjects' ages ranged from 18 to 60; 3 subjects were left-handed or ambidextrous. None had previous telerobotic training. All but 4 had previous experience with video or computer game controllers, and all but 2 used a computer at least three hours a day. They received $40 compensation for participation in the entire experiment, or $10 per hour completed.

3.3.8 Procedure

The experiment was conducted in the MIT MVL's VR Lab and took place in 3 sessions (the first lasting 2 hours and the others lasting 1 hour) spread over 3 days. Table 3.4 outlines the content in each of the sessions. Appendix G outlines the design of each of the 18 trials that the subjects completed. Nine trials were performed under high disparity, and 9 trials were performed with the internal control mode. Each of the 3 targets was used for 6 trials.

Table 3.4 - Experiment 1 Session Descriptions

Session 1	Session 2	Session 3
• Pre-Test Questionnaire (Appendix B with results in Appendix C) • Spatial Ability Tests (CC, MRT, PSTV, PTA) • PowerPoint orientation (Appendix D) • BMC test (first time)	• Refresher PowerPoint orientation (optional) • Verbal reminder of instructions • Lesson 1 (4 trials) • Lesson 2 (4 trials) • BMC test (second time)	• Refresher PowerPoint orientation (optional) • Verbal reminder of instructions • Lesson 3 (4 trials) • Lesson 4 (6 trials) • BMC test (final time) • Post-Test Questionnaire (Appendix E with results in Appendix F)

The PowerPoint orientation introduced the objectives of the experiment, the environment and arm, and the task. Verbal reminders of the instructions highlighted what their target was with the arm and what they would be graded on (completion time, occurrences of problems, etc.)

3.3.9 Experiment Overview

Nineteen subjects completed 18 telerobotic Fly-To trials using a virtual environment modeled after NASA's BORIS training tool. All of the subjects underwent the same treatments and measurements in the same order. The various measured variables were analyzed by a mixed hierarchical linear regression [29] using SYSTAT v12 (Systat Corporation, Chicago, IL). Each model included the same random effect (subject), which has a different hierarchical role in the analysis from that of the several fixed effects. Each model examined a set of independent variables chosen specifically for its dependent variable. Dependent variables included trial completion time, error from the best path, and occurrences of clearance violations; fixed effects included lesson, control mode, disparity condition, SpA scores, and gender. Table 3.5 lists all of the models cited in the followings sections. Lesson was treated as a categorical variable to allow for unforeseeable effects of order, fatigue, and breaks in training. Other models were attempted, but the results yielded were non-significant.

Table 3.5 - Experiment 1 Regression Model Components

Dependent Variable	Fixed Effects
LOG(Fly-To Segment Completion Time)	Lesson, Control Mode, Disparity, Age, BMC score
LOG(Fly-To Segment Completion Time) in External Mode	Lesson, Disparity
LOG(Alignment Segment Completion Time)	Lesson, Control Mode, PSVT score, PTA score, Gender
LOG(Alignment Segment Completion Time) in External Mode	Lesson, PSVT score, Gender
Fly-To Continuous Movements	Lesson, Control Mode, Disparity
Fly-To Continuous Movements in External Mode	Lesson, Disparity, Disparity x BMC score group
Alignment Continuous Movements	Lesson, Control Mode, PSVT score
Fly-To Changes in Direction in External Mode	Lesson, Trial, Control Mode
LOG(Fly-To Average Movement Duration)	Lesson, Trial, Control Mode, LOG(PTA score), previous experience with controllers (binary)
LOG(Alignment Average Movement Duration)	Lesson, Trial, Writing Hand
LOG(Fly-To Path Error)	Lesson, PSVT score, Age
LOG(Fly-To Path Error) in External Mode	Lesson, PSVT score
LOG(Alignment Path Error)	Lesson, PSVT score
LOG(Alignment Path Error) in External Mode	Lesson, PSVT score
Fly-To % of Time Spent Moving	Lesson, Trial, Control Mode, BMC score, PTA score
Fly-To % of Time Spent Moving in Internal	Lesson, Disparity
Fly-To Clearance Violations	PSVT score, Disparity

In each case, the residuals were tested for normality (using a one-sample K-S test) and for equality of variances across predicted value. In these mixed hierarchical regressions, subject was treated as a random effect. The p-value listed for a parameter estimate is the fraction of its distribution, based on the inferred error interval, which overlaps the value 0.

The plots of measured variables were created from original data. Their error bars show the standard error of the mean, not the error in the mean estimated from the regression model. The latter are generally smaller because they take account of systematic variations in conditions and the underlying estimated effects. That greater input reduces the residual estimate of error due to random and unmodeled fluctuation.

3.4 *Results*

3.4.1 Spatial Ability and Bimanual Control Scores: Descriptive Statistics

The descriptive statistics of the spatial ability and bimanual control test scores are presented in Table 3.6, along with statistics for the astronauts (n = 40) that were tested by Liu et al in a separate study of astronaut spatial skills and performance [19], reviewed in Section 2.5.2). Kruskal-Wallis tests found no statistical differences between the MRT (p = 0.389), PTA (p = 0.245), or PSVT (p = 0.256) scores of the subjects participating in this study and the astronauts.

Table 3.6 - Spatial Ability Test Score Descriptive Statistics

Test	Mean (Median)	SD	Max	Min	Astronaut Mean	Astronaut SD
CC	26.00 (28.50)	9.00	40	10	N/A	N/A
MRT	19.27 (19.00)	7.32	34	4	17.28	8.74
PTA	20.65 (20.56)	3.24	28.10	15.83	19.61	3.40
PSVT	15.82 (15.50)	5.14	24	7	18.03	6.70
BMC	25.10 (27.86)	9.44	37.68	4.25	N/A	N/A

The subjects' MRT and PTA scores were roughly normally distributed, but their PSVT scores were roughly uniformly distributed. The only significant correlations found between separate test scores were between CC and PTA (Figure 3.7a, R = 0.495, p = 0.031), MRT and PTA (Figure 3.7b, R = 0.578, p = 0.047) and BMC and MRT (Figure 3.7c, R = -0.473. p = 0.029). Previous MVL studies [27] found a higher correlation between PTA and PSVT (R = 0.577) than the insignificant correlation (R = 0.200) found is this study. That correlation is not surprising because both tests measure perspective-taking ability. The current study found the same lack of significant correlation within each gender.

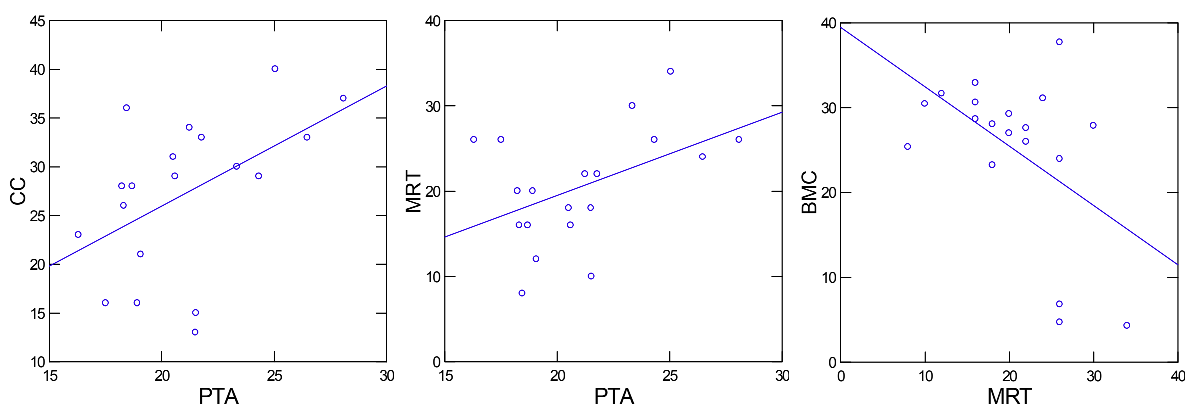

Figure 3.7 - Score Correlations: (a) CC vs. PTA, (b) MRT vs. PTA (c) BMC vs. MRT

Figure 3.7c suggests a negative correlation between MRT and BMC. All subjects with below average (less than 19.27) scores on the MRT did well on the BMC, but subjects with high MRT scores were inconsistent on the BMC. None of the other SpA test scores suggested a source for these differences between these groups. There was, by contrast, there was a positive correlation ($R = 0.662$, $p < 0.001$) between the Astronaut MRT scores and performance on a bimanual control exercise given during ART. [13] We have no explanation for this discrepancy.

Previous MVL experiments, as well as other research, have found significant gender-effects in SpA scores. Kruskal-Wallis tests showed that female astronauts (Group 0 in Figure 3.8) tested by the MVL had lower scores on the MRT (Figure 3.8a, $p < 0.001$) and PSVT (Figure 3.8b, $p = 0.001$). However, there were no significant gender-differences found in the subject group used in this experiment (MRT: Figure 3.8b, $p = 0.435$, PSVT: Figure 3.8d, $p = 0.138$). The female MIT subjects had significantly higher scores on the MRT than the female astronauts ($p = 0.029$), but the corresponding differences in PSVT scores were not significant ($p = 0.364$). The male MIT subjects' scores were not significantly different from those of their astronaut counterparts on any of the tests (MRT $p = 0.921$, PSVT $p = 0.225$, PTA $p = 0.450$).

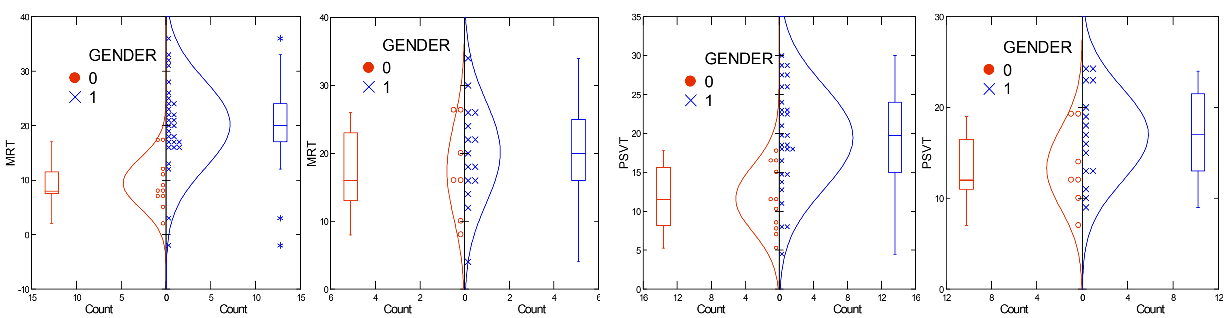

Figure 3.8 - Differences in Spatial Ability Scores by Gender
MRT for (a) Astronaut and (b) MVL groups; PSVT for (c) Astronaut and (d) MVL groups

3.4.2 Learning Effects

The subjects' performance in several areas improved over the course of the experiment. Some metrics even showed improvement over the break between sessions 2 and 3 (Lesson 2 to Lesson 3). The subjects' trial time decreased for both the Fly-To (Figure 3.9a, $p = 0.002$) and Alignment (Figure 3.9b, $p < 0.001$) segments. Subjects improved significantly between lessons

[13] The design of bimanual control exercise given during the ART is considerably different from the BMC; scores on the two cannot be directly compared.

2 and 3. Figure 3.9c shows that the subjects' path error also decreased (p = 0.008), but it did not change significantly between the second and third lessons.

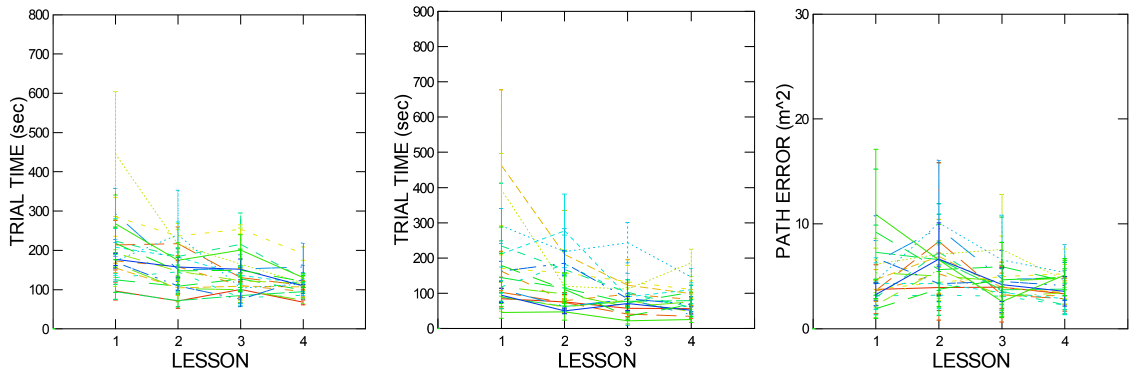

Figure 3.9 - Effect of Learning throughout the Experiment
(a) Fly-To Trial Time, (b) Alignment Trial Time, and (c) Fly-To Path Error vs. Trial

Figure 3.10a and Figure 3.10b show that, as the experiment progressed, subjects made fewer but longer movements instead of repeated stops and starts of the arm's motion (p = 0.037, p = 0.003). This is a useful skill emphasized in GRT Training; limiting the number of starts and stops will reduce oscillations of the arm and its payload. Using long continuous movements was not emphasized during the PowerPoint training before the experiment began; it is interesting that the subjects began to develop this skill on their own. The hierarchical mixed regression model showed that the subjects improved significantly between lessons 2 and 3 for both measures.

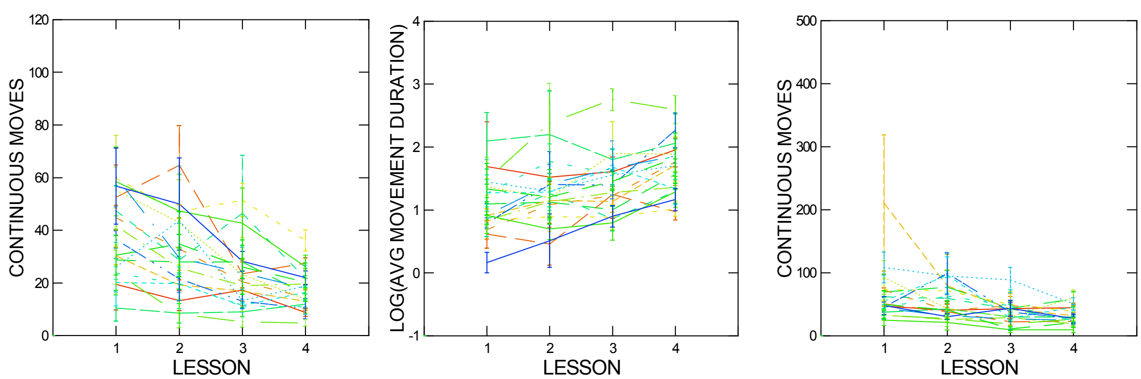

Figure 3.10 - Effect of Learning throughout the Experiment
Fly-To (a) Continuous Moves and (b) Avg. Move Duration; (c) Alignment Continuous Moves

Figure 3.10c shows that subjects made shorter movements during alignment throughout the experiment (p = 0.004). They likely struggled initially to determine how to align the arm, but their technique improved with practice; in the later trials, they could make fewer movements and accurately align on the first or second try, rather than on the sixth or seventh try.

As shown in Figure 3.11a, the percentage of time that subjects spent moving during the Fly-To segment increased throughout the experiment ($p < 0.001$). Figure 3.11b shows that the percentage of moving time that was spent making translational movements along two or more axes increased throughout the experiment ($p < 0.001$). There were no significant improvement between lessons during the alignment segment for either measure.

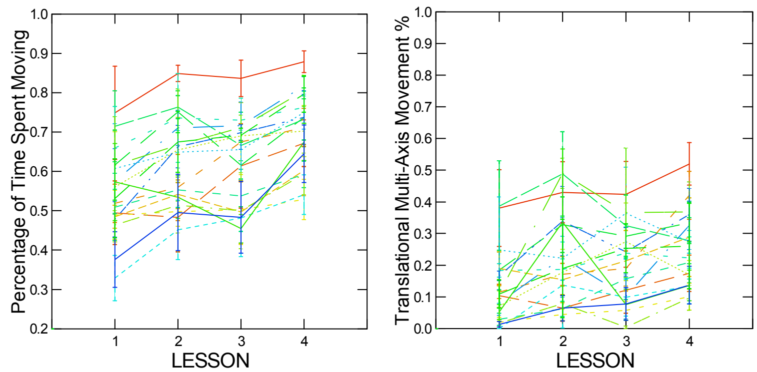

Figure 3.11 - Fly-To (a) Moving and (b) Translational Multi-Axis Percentages

3.4.3 Spatial and Bimanual Control Ability Effects

Our first hypothesis was that subjects with high SO, SV, and BMC skills would perform better than the other subjects at the telerobotic tasks. The following sections detail the results found broken down by performance area.

3.4.3.1 Path Error

The average path error variable measured how well subjects were able to find the shortest path to the target and align without large translational drift. Regression modeling[14] revealed that during the first 2 lessons, subjects with above average PSVT scores had smaller path errors than subjects with lower scorers (Figure 3.12a, $p = 0.023$) during the Fly-To Segment. By the third lesson, the lower scoring subjects were no longer significantly different from the higher scorers. Perhaps the low scoring subjects take longer to grasp the environment and their task. Also, all subjects had a break between lessons 2 and 3, but perhaps the low scores benefited more from the time to think about what they had learned. Subjects with above average PSVT scores also had smaller path errors during the Alignment segment (Figure 3.12b, $p = 0.021$).

[14] This analysis included only data for the target berths on the table; all subjects had much higher errors on trials with the target on the aft wall because they had to maneuver the arm up over the workbench.

The 3 subjects who had the highest path errors during the Fly-To segment, regardless of target location, had significantly lower PSVT scores than the others (Figure 3.12c, Kruskal-Wallis test, p = 0.007). To distinguish the subjects with the highest path errors, we used a ranked each subject's average path error for each target location, summed the ranks, and used a Friedman Test to compare them. Subjects with the smallest errors on the Fly-To segment did not necessarily have the smallest errors on the Alignment segment (Friedman Tests, Lesson 1 p = 0.208, Lesson 4 p = 0.425).

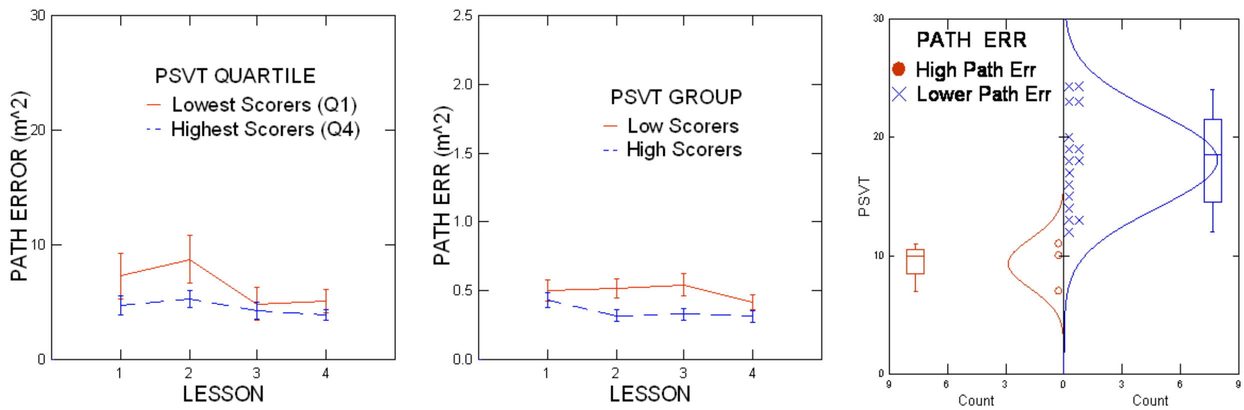

Figure 3.12 - Perspective Taking Effects on Path Error
(a) Fly-To and (b) Alignment Segments; (c) PSVT Differences for Highest Errors

3.4.3.2 Percentage of Time Spent Moving

BMC scores were bimodal; a mixed regression model showed that subjects with scores greater than 15 spent a larger percentage of their time moving the arm during the Fly-To segment (Figure 3.13, p = 0.05).

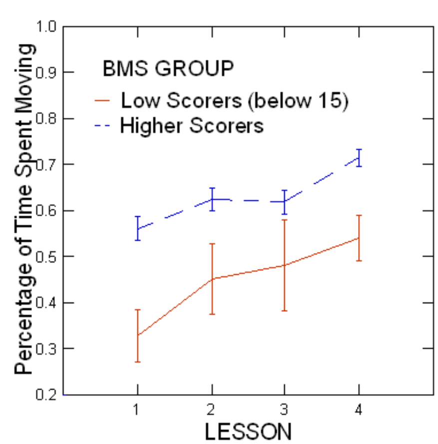

Figure 3.13 - Effect of BMC Score on Percentage of Time Spent Moving

3.4.3.3 Clearance Violations

Subjects were required to maintain at least 0.6 m of clearance between the arm and all other parts of the environment. Figure 3.14a shows the frequency of each type of clearance violation or collision.[15]

Over 40% of all clearance violations were between the lower arm boom (the segment between the elbow and the end-effector) and one of the walls of the environment (coded as 01000000 in the figure). This was expected since the location of the arm's base made it easy for the elbow to get too close to the forward wall. Although clearance violations between the lower arm link and a wall were the most common type, actual collisions between them were rare. Collisions most often involved the lower boom and the end-effector (coded as 10000100 and 10010011). The four remaining types of collisions were of the lower boom or end-effector with the walls or the table. Those clearance violations were followed by a collision less than 10% of the time.

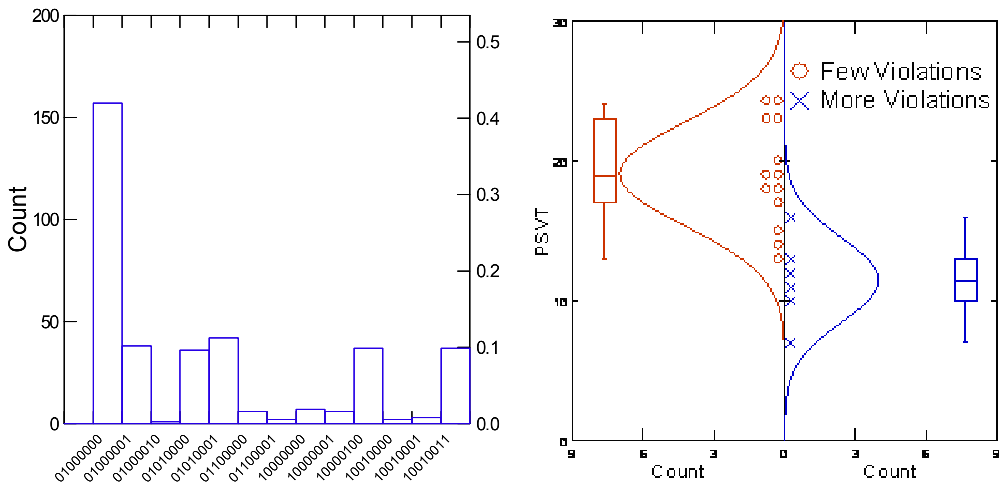

Figure 3.14 - Violation Types (left); PSVT scores for Clearance Violators (right)

Under high disparity, 6 subjects had an average of more than one violation per trial; under low disparity, only 1 subject did. The effect of disparity on the occurrence of clearance violations may have been due to the locations of the cameras and the arm. The low-disparity cameras gave a clear view along the forward wall (the object most frequently implicated in clearance

[15] Clearance violations and collisions were coded using a 2-2-4 digit binary code. The first 2 digits represented whether it was a clearance violation (01) or collision (10). The second 2 digits represented the part of the arm involved (00 = lower arm link, 01 = end-effector, 10 = upper arm link). The final 4 digits represented the part of the environment arm involved (0000 = walls, 0001 = table, 0010 = solar panel).

violations). This allowed easy determination of the distance between the wall and other objects. The high-disparity cameras showed a view that was closer to perpendicular with the forward wall, which made clearance determinations much more difficult. The 6 subjects with more violations under high disparity had significantly lower PSVT scores than the other subjects (Figure 3.14b, $p < 0.001$).

3.4.3.4 Target Distance Estimation

In addition to the ability to judge clearances discussed in the previous section, another measure of ability to estimate distance was performance at positioning the end-effector 1.5 m above the target box. The subjects used the 1 m length of the end-effector as a guide. A non-parametric Friedman test showed significant performance differences between subjects ($p = 0.028$), but neither performance nor tendency to over/under-estimate correlated with differences in SpA test–scores. The subjects' estimates did not vary significantly between lessons or between trials within a lesson.

3.4.4 Camera- vs. Control-Frame Disparity Effects

Our second hypothesis was that large (greater than 90°, but not 180°) disparities would negatively affect performance and that subjects with better spatial abilities would perform better with large disparities than their lower-scoring counterparts. Fixed disparity conditions occur only in external mode when both the control- and camera-frames remain fixed; in internal mode, the orientation of the control frame is constantly changing as the arm moves. An effect of disparity was found during the Fly-To segment of the external mode trials,[16] and there were 2 measures where SO or SV scores affected performance. An effect was also found during the Fly-To segment of the internal mode trials; although the disparity conditions were not fixed, the average disparity during a trial was either below or above 90°.

3.4.4.1 External Control Mode

Under high disparity, subjects made more changes in direction ($p = 0.003$) and those with high (above average) PSVT scores made fewer changes than those with lower scores (Figure 3.15a,

[16] During lessons 1 and 2, subjects were only exposed to either the low or high disparity case (when using the external control frame). These sessions were subsequently excluded from disparity analysis.

p = 0.002). There were no significant differences between high and low-scoring PSVT subjects under low disparity. Subjects also made more continuous movements with the high disparity cameras (p = 0.048), indicating less fluid motion with more starts and stops. This is potentially interesting because sudden inputs to PDRS or SSRMS can cause oscillations or poor control of the payload.

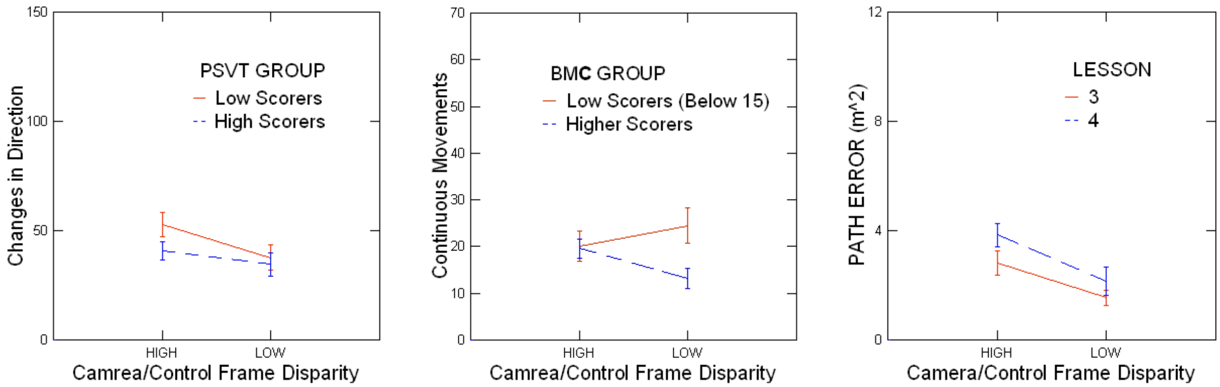

Figure 3.15 - Effect of Disparity on Fly-To Performance in External Mode
(a) Changes in Direction, (b) Continuous Movements, (c) Path Error

Figure 3.15b shows the significant cross-effect between BMC score group[17] and disparity on the number of continuous movements (p = 0.046). There was no statistical difference in the number of continuous movements made by low BMC scoring subjects as between disparity levels; high scorers made more movements under high disparity than under low. Figure 3.15c shows subjects had a less efficient path to the target under high disparity than under low disparity conditions (p = 0.001).

3.4.4.2 Internal Control Mode

To use the internal control mode efficiently, the operator must continuously update a mental map of the control frame's location and orientation. With the initial arm position and target locations that were used in this experiment, the disparity between the camera- and control-frames in internal mode was usually less than 90° if the Cameras 1 and 4 were in use (or greater than 90° if Cameras 2 and 3 were in use). Therefore, performance was negatively affected under the high disparity condition during the internal mode trials.

[17] BMC scores were bi-modally distributed; there was a gap between scores of 10 and 20. Subjects with scores below 15 were designated as group 0.

As expected, subjects did spend a higher percentage of their time moving under the low disparity condition (Figure 3.16a, Kruskal-Wallis test, $p < 0.001$) than under the high disparity condition, and a higher percentage of their movement time translating along multiple axes (Figure 3.16b, Kruskal-Wallis test, $p = 0.038$).

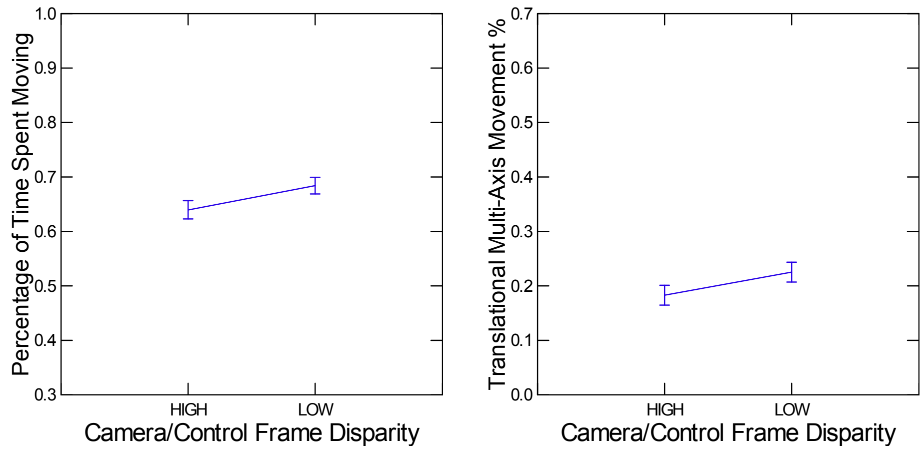

Figure 3.16 - Effect of Disparity during Internal Control Mode Trials
(a) Percentage of Time Spent Moving, (b) Translational Multi-Axis Percentage

3.4.5 Control Mode Effects

Our third hypothesis was that subjects with high SO, SV, and BMC skills would perform better than their counterparts when performing a segment using the atypical control mode (i.e. the Fly-To segment using the internal control mode). Subjects were not allowed to switch the control mode during a trial and the performance measures confirmed that all subjects had anticipated [19] difficulties when performing the given task segment with the less-intuitive control mode.

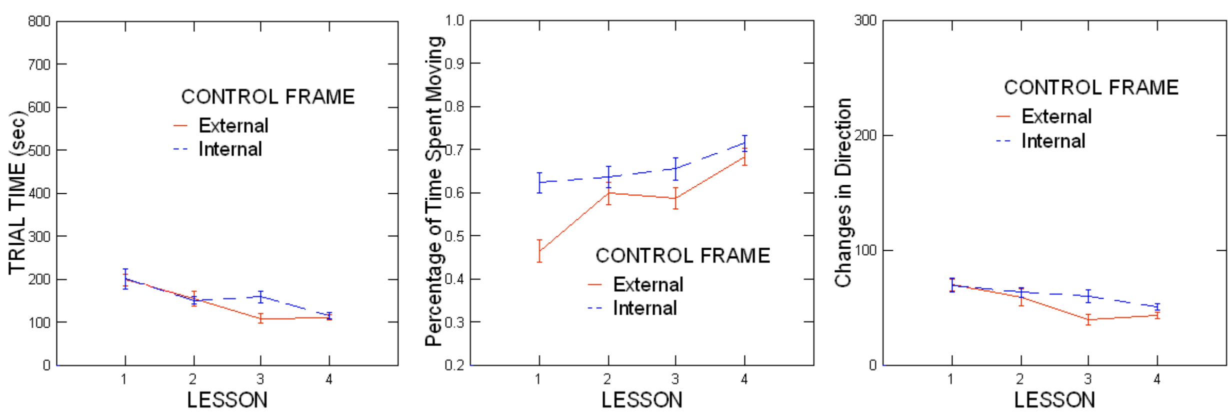

Figure 3.17 - Effect of Control Mode on Performance
Fly-To (a) Trial Time (b) Percentage of Time Spent Moving, and (c) Changes in Direction

Figure 3.17a shows that, during lesson 3 (the first lesson of the third session), subjects took longer on the Fly-To segment with the internal mode ($p = 0.011$) than with external. Figure 3.17b shows that, during the Fly-To segment in lesson 1, subjects spent a larger percentage of their time moving the arm when using internal mode ($p < 0.001$) than with external mode. This was not due to an increase in the number of control reversals in the less-intuitive internal mode; Figure 3.17c shows there was, in fact, no significant difference in the number of changes in direction, and the error from the best path was actually lower when using when using the internal control mode.

High scoring subjects on the spatial and bimanual control ability tests did not perform significantly differently from low scorers when using the "wrong" (internal) control mode during the Fly-To segment. However, there were performance differences during the Alignment segment. Subjects with above average scores on the PSVT took more time to align with the target when using the external control mode than low scorers (Figure 3.18a, $p = 0.011$). This is contrary to expectation. Additionally, high PSVT scorers took more time to complete the alignment segment regardless of the control mode being used (Figure 3.18b, $p = 0.015$) and made more continuous movements ($p = 0.017$). Observations made during the experiment suggest that this anomaly arose because the high-scoring subjects' were more insistent on being precise in their alignments.

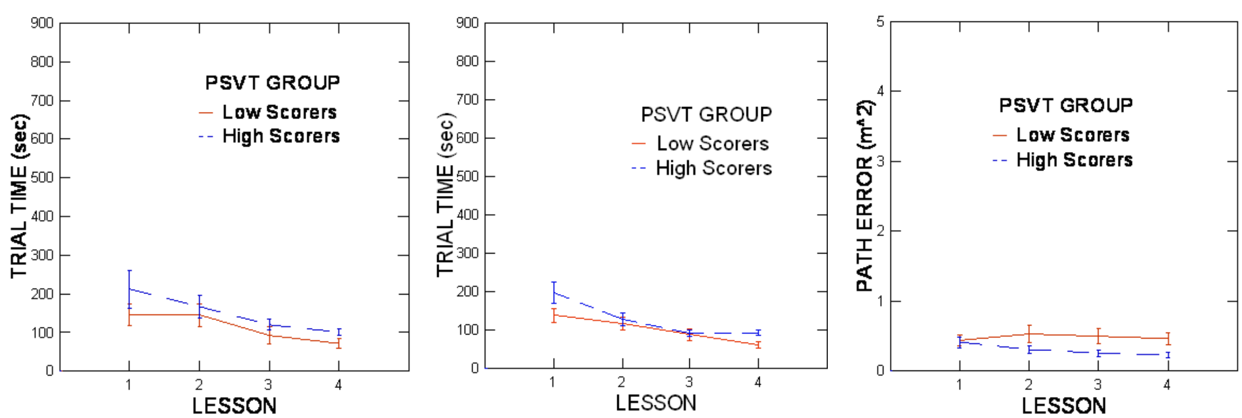

Figure 3.18 - Effect of SpA on Performance with the Atypical Control Mode
(a) Completion Time in External Mode and (b) Overall; (c) Path Error

Figure 3.18c shows that, as expected, subjects with above average PSVT scores had lower path errors ($p = 0.011$) when using the external control mode to align with the target.

3.4.6 Other Effects

Female subjects took longer to complete the alignment segment than males (Figure 3.19a, p = 0.05). All subjects were required to manipulate the THC with their left hand and the RHC with their right. We wondered if writing handedness would influence performance. We found that the 3 left-handed subjects had longer movements than the right-handed subjects during Alignment (Figure 3.19b, p = 0.048). With so few left-handed subjects (and the large errors indicated), any suggestion that handedness plays a significant role would be speculative.

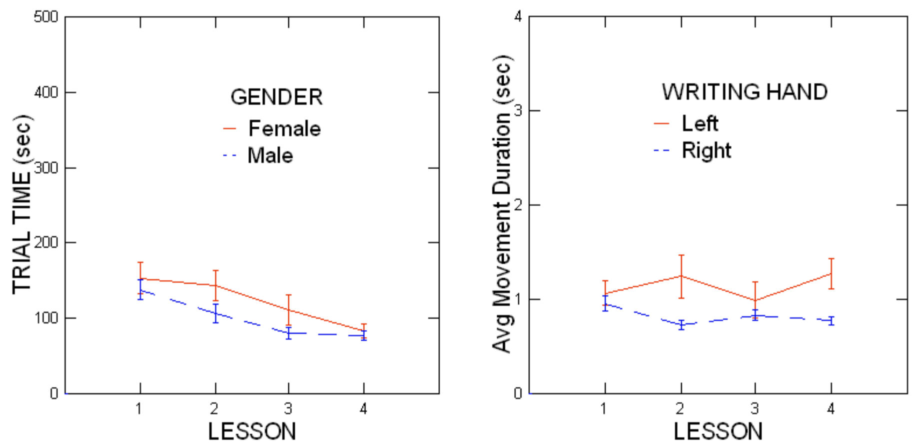

Figure 3.19 - Performance Effects of (a) Gender and (b) Writing Hand

3.5 *Discussion*

3.5.1 Predicting Overall Performance

NASA trainers could benefit from being able to predict an astronaut's overall training performance from spatial ability scores. This experiment was not intended to be detailed enough in scope to predict performance throughout the entire robotics training flow. However, several useful metrics of performance on basic tasks were developed and the data can be applied to improve training, as discussed in Section 6.

Some subjects consistently had good (or poor) performance on the Fly-To segment across multiple measures, but SpA scores did not suggest a way to predict who the best (or worst) overall performers were. To distinguish the high performers from the low on several measures (trial time, path error, moving percentage, average movement duration, and translational multi-axis movement percentage), we ranked each subject's performance for each measure, summed the ranks, and used a Friedman Test to compare them. Some subjects performed significantly worse (Friedman, Lesson 1 $p = 0.006$, Lesson 4 $p < 0.001$), but separate Kruskal-Wallis tests for each SpA test showed that these subjects did not have significantly different scores from the rest. This may be because only a few of the measures related to a common SpA test.

3.5.2 Effect of Control Frame and Disparity

We expected that performance would depend on the angular disparity between the orientation of the camera- and the control-frames. We found that disparity played a smaller role in performance than control mode did. The mental calculations needed to transform the arm commands into expected motions in the camera-frame are an intrinsic part of successful arm-maneuvers; in internal mode, this relationship is constantly changing, whereas in external mode, there were only two fixed conditions. It is not surprising, then, that measures of movement quality (e.g. changes in direction, path error) varied with disparity.

3.5.3 Clearance Violations

One of the most important skills in the GRT is the ability to accurately determine the distance to an obstacle. The clearance limit exists because there is a lag between the time a command is specified with the hand controllers and the time the arm responds. During this lag, the arm will travel a maximum distance of 0.6 m. There was a visual warning ('CLEARANCE VIOLATION') whenever the subjects brought the arm within 0.6 m of any object. The rarity of collisions during the experiment can likely be attributed to this warning and fact that the MVL DST arm has a much smaller response lag than the BORIS arm. Clearance violation warnings were not issued when the arm was about to collide with itself, which was the most frequent type of collision. As noted earlier, lower scoring PSVT subjects had a many more clearance violations.

We considered disabling the clearance violation warnings for part of the training[18] to determine their impact on performance. Preliminary tests, however, showed that the warnings became a "crutch" and turning them off significantly affected performance. During GRT training, instructors intentionally limit the use of such aids in order to prevent this scenario from occurring. The PDRS and SSRMS do not have physical sensors that could provide warnings to operators about clearance, but the rarity of collisions after violations warnings during the experiment supports the belief that including such capabilities on future arms could be beneficial.[19]

3.5.4 Estimation of Distance from the Target

None of the SpA scores significantly related to ability to estimate the 1.5 m distance from the target. One reason for this may be that subjects discovered a non-spatial trick for judging distance. Anecdotal evidence suggests that, after estimating the distance on the first trial, many subjects found visual cues to use on subsequent trials. A commonly mentioned strategy was to memorize the position of the crosshairs with respect to the black line on the grapple target at the 1.5 distance during training trials. (During GRT training, a similar line is available and is normally used to determine distance from the target before engaging latches.)

3.5.5 Spatial Ability Scores and Gender

We found few gender-effects on performance, perhaps because the females and males in this experiment did not have significantly different MRT and PSVT scores. The other test scores and previous experience (as reported on the pre-test questionnaire) do not suggest any explanation for the absence of gender-effects when they have been reported in similar settings elsewhere.

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[18] The considered options included turning off the warnings for both lessons in the third session or for the 4th lesson. During the preliminary testing, the warnings were turned off for the 4th lesson only.

[19] D. Burbank. NASA Astronaut, Johnson Space Center, personal communication.

4 Experiment 2

4.1 Objectives

This experiment was performed in two parts: a primary operator training experiment and a secondary operator testing experiment. The objectives of the primary operator experiment were:

1. To investigate the effect of spatial abilities on performance.
2. To investigate the interaction of spatial abilities and camera/control frame disparity.
3. To determine if subjects with better spatial ability scores distribute their gaze between the monitors differently from those with lower scores.
4. To identify early training performance predictors that could help NASA customize telerobotic training.

The objectives of the secondary operator experiment were:

1. To determine the effectiveness of signal detection theory (SDT) as a model for discrimination of secondary operator errors (What are the probabilities of correct detections or false alarms and how do they vary with payoff?)
2. To study secondary operator performance using a more realistic ISS virtual environment, including inverted cameras, and assess the role of spatial abilities.

4.2 Hypotheses

We hypothesized that:

- Subjects with better SO, SV, and BMC skills would perform better at primary operator tasks than those less skilled regardless of disparity condition.[20]
- Subjects with better SO and SV skills would perform better as a primary operator when there is a large (greater than 90°) disparity between camera- and control-frame orientation.
- Subjects with poor spatial abilities would fixate on a single view (instead of spreading dividing their visual attention over all of the monitors), and would spent more time than others analyzing paper maps of the virtual environment during primary operator tasks.
- Subjects with better SO and SV skills would perform better during secondary operator tasks than those less skilled.[21]

[20] Primary operator performance was defined by several metrics including trial completion time, percentage of time spent moving, number of problems that were encountered, path error, and number and duration of continuous movements

- A secondary operator's P(H) and P (FA) can be moved to a different point on the ROC curve by changing the payoff rule.
- Subjects with the worst performance as primary operators would also have the worst performance as secondary operators.

4.3 Methods

4.3.1 Primary Operator Experiment

All NASA astronauts train as primary operators before becoming secondary operators. The primary operator portion of the experiment was therefore included to train our naïve subjects (and provide refresher primary operator training to returning subjects) before the secondary operator experiment. This also provided an opportunity to include some fly-to route planning techniques used during NASA GRT that were not incorporated into Experiment 1 training, as described in the next section.

4.3.1.1 Primary Operator Task

Subjects were taught to use landmarks in the environment (such as the grid on the walls) in order to accurately maneuver the arm to a point specified on printed maps. Figure 4.1 shows an example of a map used for positioning; the open circle represents the end position. For this example, when looking from camera 2 (or 3; the view-path is represented by the dotted line), the correctly positioned end-effector tip would appear to be in front of the center of the port wall (or starboard wall, respectively; this point is represented by the closed circle). A second map (not shown) displayed the desired height in a view from the forward wall. In addition to specifying a target position, an end-effector orientation (pitch or roll angle) was also printed on the maps.

Subjects were to determine the best route to the target as quickly as possible while maintaining a minimum clearance of 0.6 m from all objects and avoiding other problems. All subjects used the same starting position for all trials. Each trial was treated as a single Fly-To segment and performed using external control mode. Since this was a training experiment, the subjects' final position and orientation errors were numerically displayed to provide feedback after each trial.

[21] Secondary operator performance was defined by the number of correct detections, false alarms, and missed detections, payoff bonus, and whether the subject detected the event before or after it occurred.

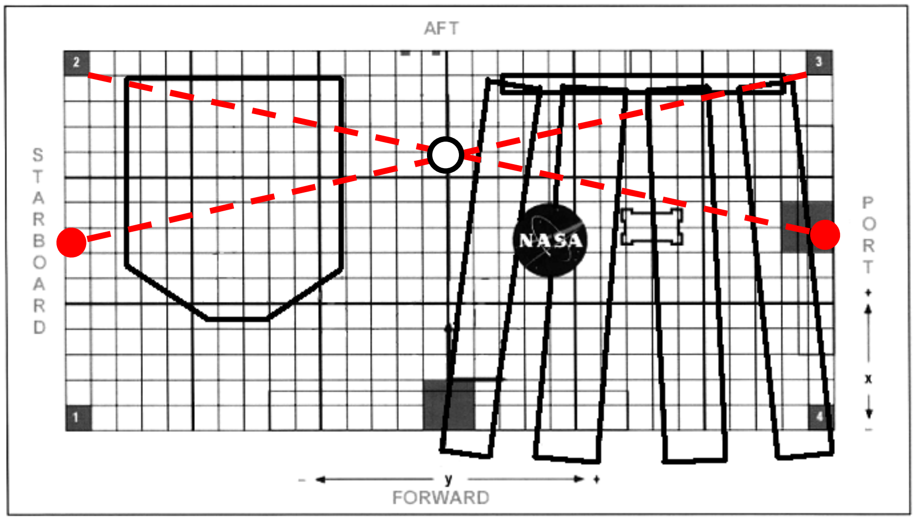

Figure 4.1 - Top View Map of MVL DST Environment with Camera View Lines

4.3.1.2 Differences in MVL DST Environment from Experiment 1

The BORIS environment from Experiment 1 (Figure 3.1) was used for the primary operator trials, with a few modifications: the table and solar arrays were relocated to positions corresponding to those used in NASA GRT training, and the target box was not used. The subject had to fly the end effector to the specified position and orientation.

4.3.1.3 Primary Operator Camera Configurations

There were 5 cameras placed as in Experiment 1: one fixed camera at each corner of the room and 1 mobile camera on the end-effector. Subjects were tested at each target position with low-disparity cameras (Cameras 1 and 4) and high-disparity cameras (Cameras 2 and 3). The view from the end-effector was always presented on the center monitor. As in Experiment 1, the subjects were not allowed to modify the cameras' orientations.

4.3.1.4 Primary Operator Performance Metrics

The same metrics from Experiment 1 were saved to Summary, Lesson, Joint Angle, and End Data Files (listed in Section 3.3.6). A Logitech QuickCam Pro 4000 web camera was used to record the subjects' face and analyze how they divided their gaze between the 4 viewing options. The recorded measures are listed in Table 4.1.[22] The experimenter played back video of the subject and visually judged which monitor they were looking at. Gaze switches were recorded by keyboard inputs to a program created in Vizard. The program automatically determined the duration of each gaze interval and computed the total time spent looking at each monitor and the paper maps and the number of switches made. Small errors presumably resulted from the experimenter's required reaction and decision times. The system was not calibrated for accuracy, but the repeatability of the analysis was tested by gathering data from the same video multiple times; the results of this were consistent within approximately 2%.

Table 4.1 - Gaze Tracking Performance Measures

Measures of performance	Description	Recorded	Calculated
Left Monitor %	Percentage of time spent looking at the left monitor		X
Middle Monitor %	Percentage of time spent looking at the middle monitor		X
Right Monitor %	Percentage of time spent looking at the right monitor		X
Paper %	Percentage of time spent looking at the map		X
Switches	Total number of gaze location transitions over a trial	X	
Switch Types (12 measures)	Number of gaze switches between each of the options (left-to-middle, paper-to-right, etc)	X	
Probabilities (12 measures)	Probability of a gaze switch between any of the four options; calculated by dividing the number of switches of that type by the total number of switches		X

4.3.2 Secondary Operator Experiment

4.3.2.1 ISS Environment

A new ISS virtual environment was developed for this portion of the experiment in order to make the tasks more realistic and challenging. As shown in Figure 4.2, the simulation included a 6 DOF arm[23] and the station's core modules and truss (as they were configured in late 2007). In order to better simulate the SSRMS, the arm was 3m longer than in the MVL DST used in the primary operator experiment, but had the same kinematic properties.

[22] The total time spent on each of the 4 options (3 monitors and the paper) as well as the total time for the task were all recorded, but not used in analysis. The percentage of total time was used instead to account for the fact that subjects spent different amounts of time performing each task.

[23] The ISS' arm is actually a 7 DOF system, but the extra DOF makes predicting movements more complex. To keep the task's difficulty fair, given the subjects' relatively low training level, the same 6 DOF arm from their previous training was used.

So that our results would be generalizable beyond one task geometry, the environment was modified slightly between the lessons; in Lessons 1 and 2, the Shuttle (Figure 4.3) was docked to the modules, and the arm's payload varied between the Harmony module in Lessons 1, 3, and 4 and an astronaut (Figure 4.3) in Lesson 2.

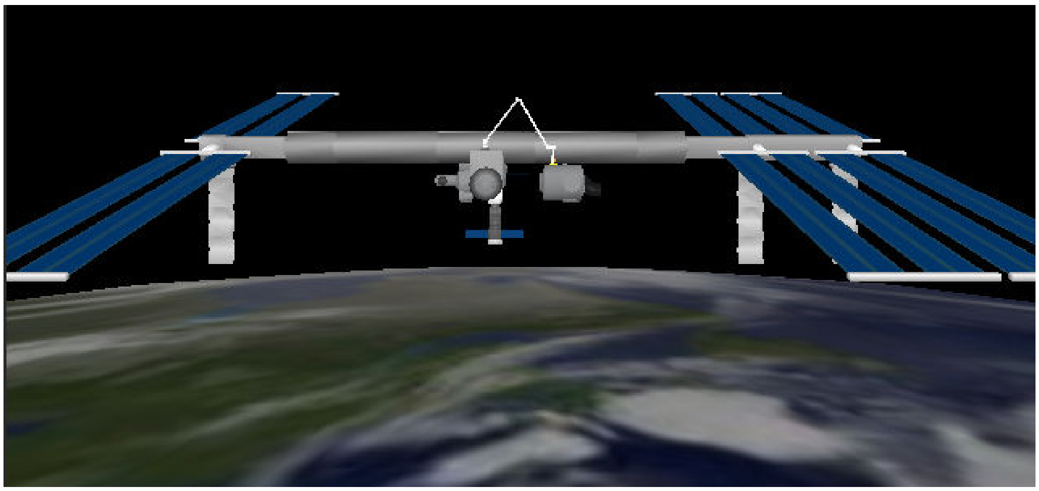

Figure 4.2 - ISS Virtual Environment (Lesson 3)

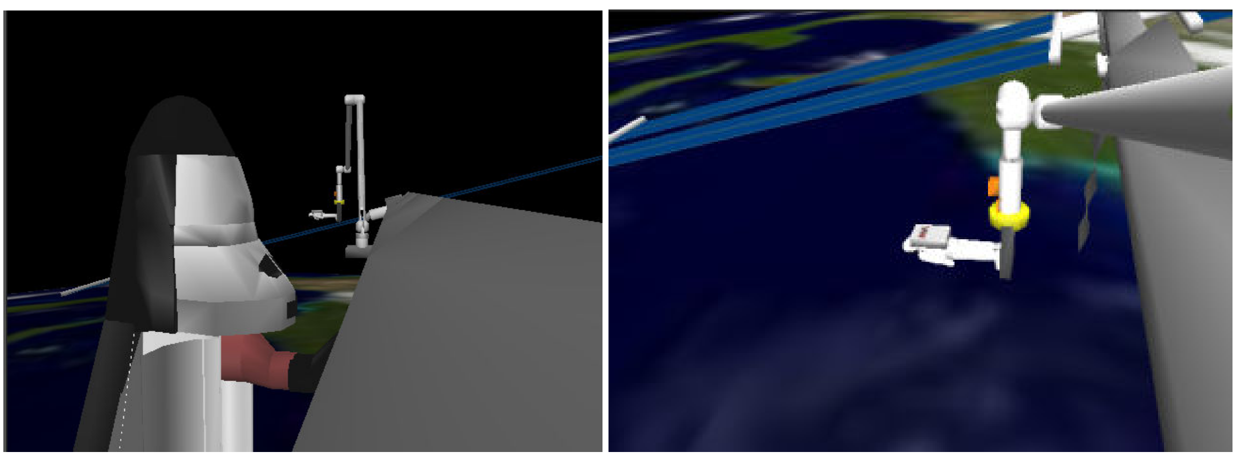

Figure 4.3 - ISS Virtual Environment with (a) Shuttle and (b) Astronaut

4.3.2.2 Secondary Operator Task

The subjects first listened to a recording in which a virtual primary operator described a planned arm fly-to movement. They then watched the displays as the virtual primary operator performed the task. The subjects were instructed to push a button to stop the arm if they observed any of 3 types of problems developing: clearance violations, singularities, or unexpected motions. Detailed instructions are shown in Appendix N.

Clearance violations occurred when the arm came within 0.6m of a module or the truss. Singularities occurred when the arm reached any of three configurations (elbow, wrist yaw, or wrist roll singularities) where the arm loses one or more degrees of freedom and the software can no longer compute the next point along the trajectory. Unexpected motions occurred when the arm's motion differed from the plan that was communicated to the subject by an audio recording. Clearance violations and singularities could be anticipated and addressed before the problem actually occurred. Subjects were expected to react to unexpected motions before the virtual "primary operator" did (characterized by stopping and reversing the arm's motion).

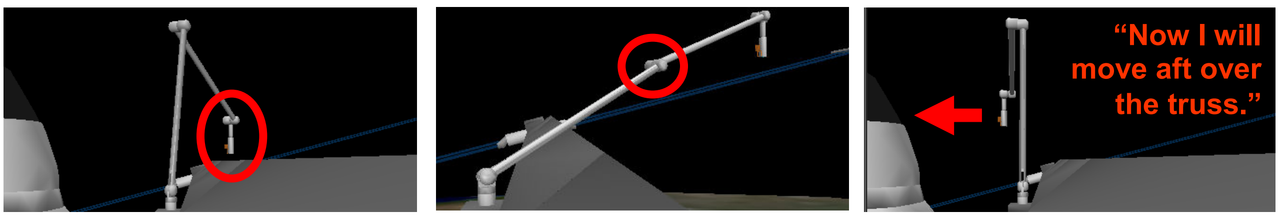

Figure 4.4 - Examples of Robotic Operation Problems
(a) Clearance Violation, (b) Elbow Singularity, and (c) Unexpected Motion

After the arm was stopped, the subjects indicated which type of problem they had detected and which parts of the arm and environment were involved. The arm's start and end-positions remained constant throughout each lesson, but the path taken differed between trials. Each trial had one or no problems; each lesson had 2 trials of each problem type and 2 trials with no problems. This problem rate was undoubtedly higher than actually encountered during NASA operations. As a result, our secondary operators – though perhaps less skilled than their NASA counterparts – were probably more vigilant. Subjects were not told how many problems of each type to expect and were not given feedback on their performance until after they had completed the last lesson.

4.3.2.3 Camera Configurations

Figure 4.5 shows the environment's cameras; there were 4 fixed cameras on the truss, 1 fixed camera in the shuttle's payload bay, and 1 mobile camera on the arm's elbow. The pictures from the lower truss cameras were inverted relative to the upper truss cameras. The Port Upper, Elbow, and Shuttle cameras were used in Lesson 1; the Starboard Lower camera replaced the Shuttle camera in Lesson 2; and the Port Lower, Elbow, and Starboard Upper cameras were used in Lessons 3 and 4. Inverted cameras have not previously been used in our studies.

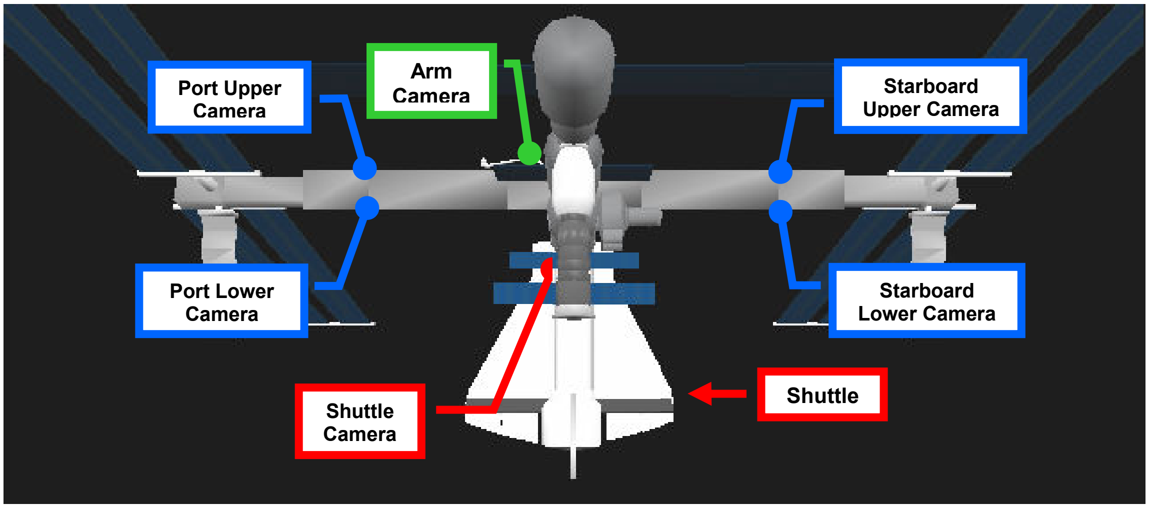

Figure 4.5 - Camera Locations in the MVL ISS Environment

4.3.2.4 Performance Metrics

Performance metrics (listed in Table 4.2) were recorded to Summary Data Files at the end of each trial. The trials were divided into 3 or 4 segments, based on the number of discrete arm movements made. The subject's response during each segment was categorized as a correct detection, missed detection, false alarm, or correct rejection.

Table 4.2 - Secondary Operator Performance Metrics

Measures of Performance	Description
Time	The time within the trial that the arm was stopped.
Problem Type	0 = clearance violation, 1 = unexpected motion, 2 = singularity
Part of Arm	The displayed options varied between lessons; included the arm's booms and the payload
Part of the Environment	The displayed options varied between lessons; included the truss, shuttle, modules
Timing	GOOD = Subject stopped the arm before a problem occurred DELAYED = Subject stopped the arm after the problem occurred FALSE ALARM = Subject stopped the arm when no problem occurred NO DETECTION = Subject failed to stop the arm when a problem occurred NO EVENT = No problem occurred and the subject did not stop the arm

4.3.3 Subjects

The experimental protocol was reviewed and approved by MIT's institutional experimental review board. 20 subjects (5 female) were tested (demographics listed in Appendix A); 9 had participated in Experiment 1 or its pilot studies.

The subjects' ages ranged from 21 to 32; 3 were left-handed. All but 5 had experience with game controllers and all but 3 reported that they previously or currently played video/computer games. One female subject's data was excluded from the secondary operator analysis because she exhibited a persistent lack of understanding of the environment. Returning subjects earned a base compensation of $30; new subjects earned $40. Subjects could also receive a cash bonus (detailed below) based on their performance on the secondary operator tasks.

4.3.4 Procedure

The experiment was conducted in the MVL's VR Lab over two sessions for each subject. Session 1 was 1 hour for returning subjects or 2 hours for naive subjects; Session 2 was 2 hours for all subjects. Table 4.3 outlines what took place during each of the sessions. Appendix Q outlines the design of the 6 primary operator trials and the 32 secondary operator trials.

Table 4.3 - Experiment 2 Session Descriptions

Session 1	Session 2
• Pre-Test Questionnaire (Appendix I with results in Appendix J) • Spatial Ability Tests (MRT, PSTV, PTA) • Primary Operator PowerPoint orientation (Appendix K) • BMC test	• PowerPoint orientation (optional refresher) • 6 Primary Operator Trials • Post-Test Questionnaire 1 (Appendix L with results in Appendix M) • Secondary Operator PowerPoint Orientation (Appendix N) • Secondary Operator Trials (4 lessons x 8 trials) • Post-Test Questionnaire 2 (Appendix O with results in Appendix P)

Returning subjects did not complete the pre-test questionnaire or the spatial ability tests; their results from Experiment 1 were used. The CC test used in Experiment 1 was not employed, to save time.

Subjects performed the first, second, and third secondary operator lessons using the first payoff rule ($0.50 for correct detections, -$0.50 for missed detections, -$0.25 for false alarms, and $0.00 for correct rejections). Half of the returning subjects and half of the new subjects (designated as groups A and B) performed Lesson 4 using a changed payoff rule with a -$0.50 penalty for false alarms while the rest of the subjects (groups C and D) continued to use the original payoff rule. The payoff rule was manipulated in an effort to shift the subjects to a different portion of their Receiver Operating Characteristic (ROC) curve as a way of validating SDT's applicability to telerobotics problem detection.

4.3.5 Experiment Overview

Twenty subjects completed 6 primary operator telerobotic Fly-To trials and 32 secondary operator observation trials. The trials used virtual environments modeled after NASA's BORIS training tool and the International Space Station, respectively.

For the primary operator trials, all of the subjects underwent the same treatments and measurements in the same order. For the secondary operator trials, there were two subgroups of subjects; one with a constant payoff rule and the second with two different payoff rules. The various measured variables were analyzed by a mixed hierarchical linear regression using SYSTAT v12. Each model included the same random effect (subject) and examined a set of independent variables chosen specifically for its dependent variable.

For the primary operator trials, dependent variables included trial completion time, error from the best path, and number of clearance violations; fixed effects included trial, disparity condition, SpA score, and gender. For the secondary operator trials, dependent variables included the number of correct detections, false alarms, and misses, overall weighted score, and timeliness of the detection (binary variable); fixed effects included lesson and subject group. Table 4.4 describes the models used for the primary operator data; Table 4.5 describes the secondary operator models. Other models were attempted, but the results yielded were not as significant as those presented in the table.

In each case, the residuals were tested for normality (using a one-sample K-S test) and for equality of the variances (using an equality of several variances test). Mixed regression p-values for hypothesis testing listed in the following sections were based on a Z-distribution.

Table 4.4 - Experiment 2 Primary Operator Regression Models

Dependent Variable	Fixed Effects
LOG(Trial Completion Time)	Trial, Disparity, PTA Score
LOG(Continuous Movements)	Trial, PTA Score
LOG(Changes in Direction)	Trial, Disparity, PTA Score
LOG(Average Movement Duration)	Trial, PTA Score
LOG(Path Error)	Trial, Disparity, PTA Score
Percentage of Time Spent Moving	Trial, PTA Score
LOG(Final Position Accuracy)	Trial, PSVT Score
Gaze Switches per Second	BMC Score, MRT Score, PTA Score, Height
Percent Time Looking at the Maps	MRT Score, PTA Score, Writing Hand

Table 4.5 - Experiment 2 Primary Operator Regression Models

Dependent Variable	Fixed Effects
Number of Correct Detections	Trial
Number of False Alarms	Trial
Number of Misses	Trial
Percentage of Hits that were Timely	Lesson, PTA Score, Gender

The plots of measured variables were created from original data. The error bars in the figures show the standard error of their raw mean and are not based on the regression model. (The variance estimates used in the hypothesis testing were smaller since they were estimated using the multiple regression model.)

Probability of correct detection and false alarm rates were calculated (along with the associated Receiver Operating Characteristic (ROC) curves) using Systat, based on the methods of Green and Swets [18].

4.4 Results

4.4.1 Spatial Ability and Manual Control Scores: Descriptive Statistics

The descriptive statistics of the spatial ability test and bimanual control test scores are presented in Table 4.6, along with statistics for the astronauts (n = 40) tested by Liu et al [19]. As with the Experiment 1 group, Kruskal-Wallis tests showed that the subjects in Experiment 2 did not have statistically different MRT (p = 0.431), PTA (p = 0.332), or PSVT (p = 0.325) scores from Liu's astronauts.

Table 4.6 - Spatial Ability Test Score Descriptive Statistics

Test	Mean (Median)	SD	Max	Min	Astronaut Mean	Astronaut SD
MRT	20.50 (22.00)	9.83	36	4	17.28	8.74
PTA	20.89 (20.16)	4.55	26.48	10.38	19.61	3.40
PSVT	15.80 (15.50)	6.20	27	5	18.03	6.70
BMC	25.52 (30.25)	9.80	33.33	-1.68	N/A	N/A

New subjects' scores were not significantly different from those of repeating subjects (Kruskal-Wallis, MRT p = 0.675, PSVT p = 0.238, PTA p = 0.425); therefore, performance differences between repeat and new subjects cannot be attributed to differences in inherent spatial skills. Repeating subjects (Group 1 in Figure 4.6a) did have higher BMC scores than new subjects (p = 0.011). Their scores had significantly improved since the first session of Experiment 1 (p = 0.031), so the improvement in BMC score is likely a practice effect. There was no statistical difference between repeating subjects original BMC scores in experiment 1 and those of the new subjects in experiment 2 (Figure 4.6b, p = 0.621).

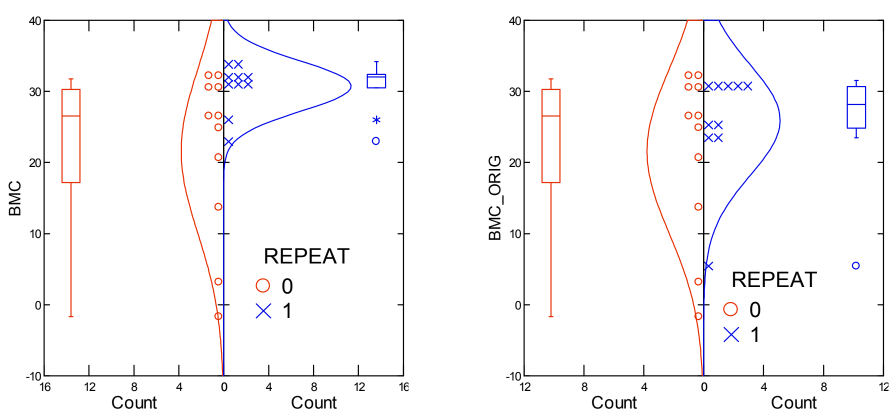

Figure 4.6 - BMC by Subject Group for (a) Second and (b) First Experiment

MRT and PTA scores were correlated (Figure 4.7a, R = 0.759, p < 0.001); unlike the subjects in Experiment 1, this group showed correlations between MRT and PSVT scores (Figure 4.7b, R = 0.612, p = 0.004) and between PSVT and PTA scores (Figure 4.7c, R = 0.760, p < 0.001), as seen in previous MVL studies [27]. Experiment 1 showed a negative relationship between MRT and BMC scores which was not formally confirmed with this study (Figure 4.7d, R = 0.417, p = 0.068). The 2 lowest BMC scorers also had the lowest MRT scores; higher MRT scorers had inconsistent BMC scores. There was also a significant correlation between BMC and PTA scores (R = 0.470, p = 0.032). Again, the 2 lowest BMC scorers had the lowest PTA scores.

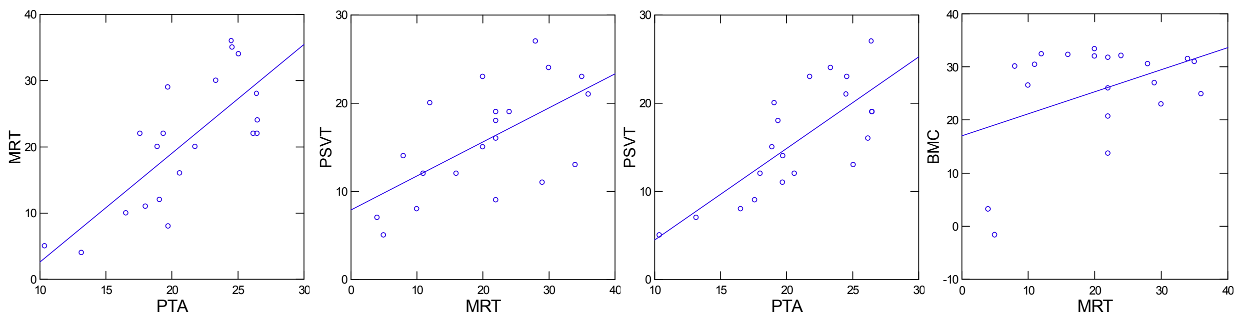

Figure 4.7 - Spatial Ability and Manual Control Test Score Correlations
(a) MRT vs. PTA, (b) MRT vs. PTA, (c) PSVT vs. PTA, (d) BMC vs. MRT

Many previous studies have found an effect of gender on spatial abilities. Experiment 1 did not find a significant gender effect, but Experiment 2 did. Table 4.7 shows scores broken down by gender for the MVL subjects and Astronauts.

Table 4.7 - Spatial Ability Test Score Statistics by Gender

	MRT		PSVT		PTA	
	MIT DST	Astronaut	MIT DST	Astronaut	MIT DST	Astronaut
Female N	5	11	5	11	5	11
F Mean	8.600	9.455	9.200	12.545	16.083	18.255
F SD	4.775	4.591	3.701	4.059	4.327	2.427
Male N	15	29	15	29	15	29
M Mean	24.643	20.241	18.000	20.103	22.497	20.117
M SD	7.558	8.105	5.251	6.360	3.415	3.602

Because we could not be sure that the data were normal, we used Kruskal-Wallis (not paired-t) tests to look for gender effects. Female MIT subjects scored lower than males on the MRT and PSVT (p = 0.003, p = 0.001). Unlike their Astronaut counterparts, they also scored lower than males on the PTA (p = 0.048). However, the two groups of females did not have statistically different scores (MRT p = 0.761, PSVT p = 0.190, PTA p = 0.841). The same was true for the male subjects (MRT p = 0.164, PSVT p = 0.613, PTA p = 0.097).

4.4.2 Primary Operator Spatial and Bimanual Control Ability Effects

Our first hypothesis was that subjects with higher SO, SV, and BMC skills would perform better than the other subjects as a primary operator performing telerobotic tasks. The following sections break down these results by performance area.

4.4.2.1 Learning Effects

Mixed regression models showed that subjects took less time to complete the later trials than the earlier ones (Figure 4.8a, p = 0.003). The 5 subjects who took longer than 400 seconds to complete the first trial had significantly lower test scores (Kruskal-Wallis, MRT p = 0.018, PSVT p = 0.002, PTA p = 0.006) than the rest of the group. Subjects with low PTA scores (below 20[24]) spent more time on each trial (p < 0.001) than subjects with high scores.

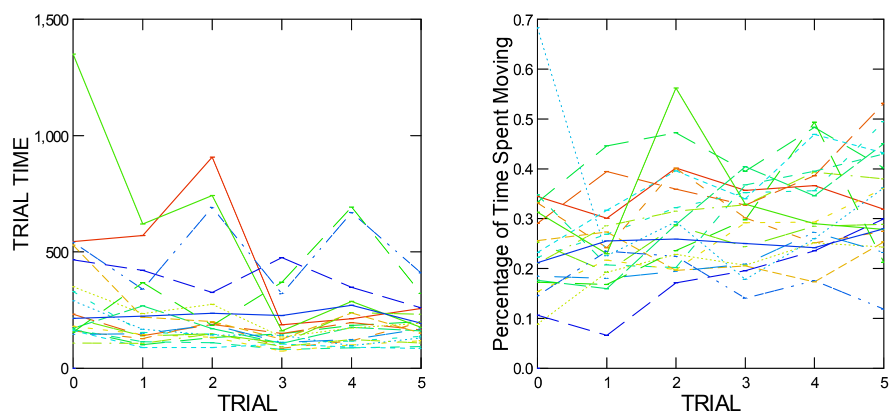

Figure 4.8 - (a) Time and (b) Percent Time Spent Moving vs. Trial

Subjects also increased the percentage of time they spent moving the arm as the experiment progressed (Figure 4.8b, p < 0.001). Subjects with PTA scores below 20 spent less of their time moving the arm than their counterparts (p = 0.008).

Figure 4.9a and b show that subjects learned to make fewer but longer duration movements instead of repeatedly starting and stopping the arm (p < 0.001, p = 0.001). The 2 subjects with

[24] Kozhevnikov defines a PTA score of 20 or higher as a demonstration of "good" 2-D PT ability.

more than 100 continuous movements during the first few trials had lower PSVT and PTA scores than the other subjects (p = 0.044, p = 0.044). The 3 subjects with average movement durations of greater than 6 seconds by the final trial had significantly higher PTA scores (p = 0.010) than the rest of the population. High PTA scorers made fewer and longer movements with the arm (p < 0.001, p < 0.001) than low scorers.

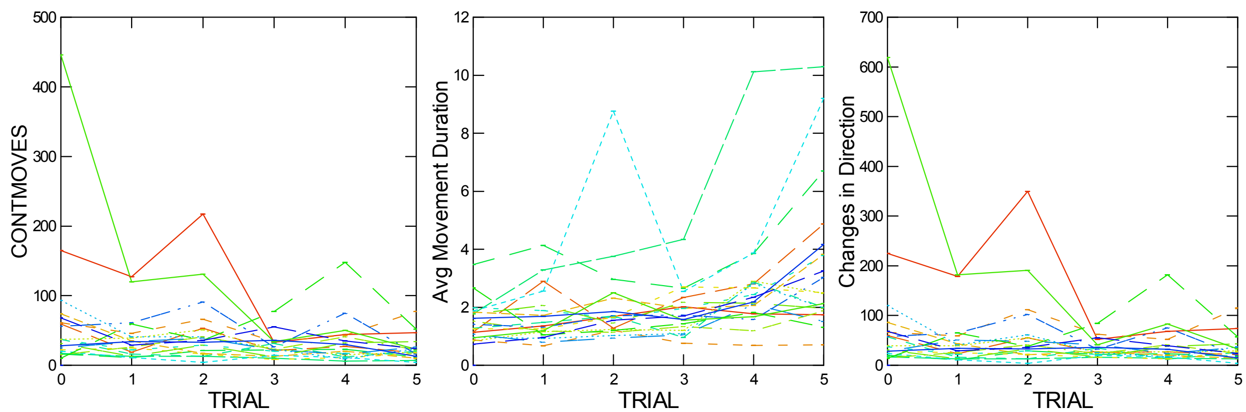

Figure 4.9 - Learning Effect on Primary Operator Performance
(a) Continuous Moves, (b) Avg. Movement Duration, (c) Changes in Direction vs. Trial

Subjects also made fewer changes in direction as the experiment progressed (Figure 4.9c, p = 0.005), which indicates that they had learned to avoid control reversals and other unnecessary movements. High PTA scores had fewer changes in direction (p < 0.001) than low scorers.

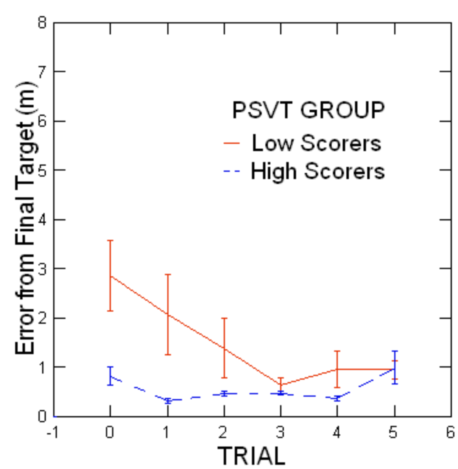

Figure 4.10 - Effect of Perspective Taking on Alignment Error

Subjects with below average PSVT scores initially had larger errors in their final position during the first three trials (Figure 4.10, p = 0.001), but those errors were no longer statistically different from those of the high scorers by the final three trials.

4.4.2.2 Clearance Violations

Clearance violations occurred much less frequently with the type of task used in this experiment than with that of Experiment 1. The 4 subjects who averaged more than 1 clearance violation per high disparity trial had significantly lower PSVT and PTA scores (Kruskal-Wallis, $p = 0.005$, $p = 0.014$) than the other subjects.

4.4.3 Primary Operator Disparity Effects

Our second hypothesis was that subjects with better SO and SV skills would perform better with large camera- vs. control-frame disparities than their lower-scoring counterparts. Subjects with high PTA scores took less time (Figure 4.11a, $p = 0.005$) and had smaller errors from the shortest path to the target (Figure 4.11b, $p < 0.001$) under the low disparity condition than under the high. The latter result was also found in Experiment 1.

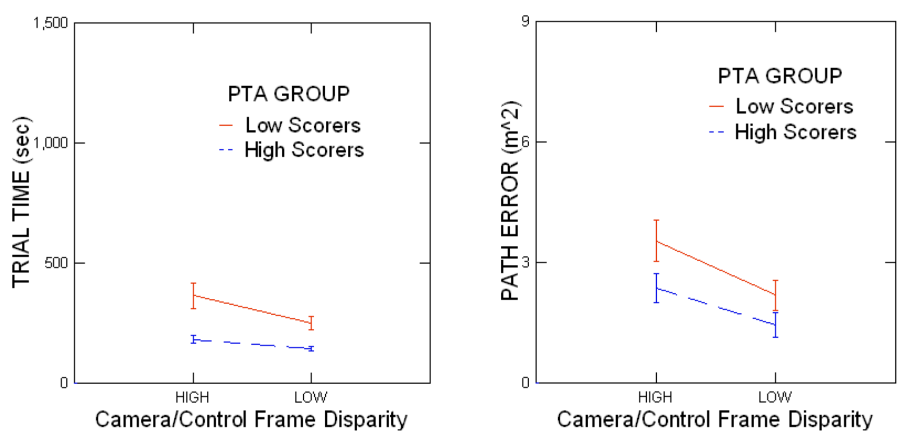

Figure 4.11 - Effect of Disparity on (a) Trial Time and (b) Path Error

4.4.4 Primary Operator Gaze Analysis

Our third hypothesis was twofold: first, we believed that subjects with low SO and SV skills would fixate on a single view while performing a primary operator task. Figure 4.12a and b show that subjects with above average BMC scores ($p < 0.001$) and PTA scores above 20 ($p = 0.009$) shifted their gaze between screens more times per second than subjects with lower scores. The second part of the third hypothesis was that subjects with low SO and SV skills would spend more time looking at the maps of the environment. Figure 4.12c shows that high PTA scorers spent a smaller percentage of their time looking at the maps ($p = 0.007$) than low scorers.

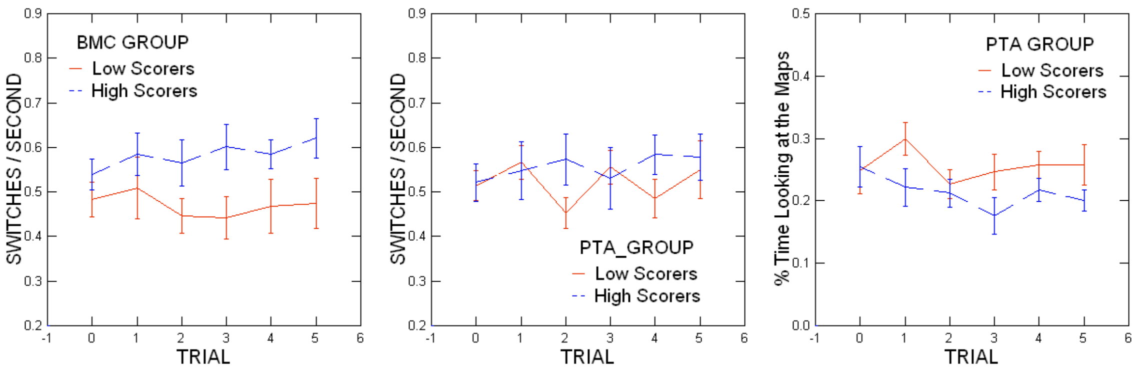

Figure 4.12 - Effect of Spatial Ability on Gaze Distribution between screens
Switches per Second vs. (a) BMC and (b) PTA; (c) Percent of Time Looking at the Maps vs. PTA

Table 4.8a gives the average probabilities of gaze transitions, with the standard errors in Table 4.8b. K-S tests showed that none of the probability distributions were significantly different from normal except those of switches from left to right and from right to left.

Table 4.8 - Mean Probabilities of Gaze Transitions (left), Std. Errors (right)

	Left	**Middle**	**Right**	**Maps**
Left		0.545	0.065	0.389
Middle	0.340		0.424	0.236
Right	0.089	0.547		0.364
Maps	0.329	0.344	0.327	

	Left	**Middle**	**Right**	**Maps**
Left		0.144	0.080	0.143
Middle	0.104		0.113	0.124
Right	0.089	0.162		0.132
Maps	0.132	0.154	0.151	

Analysis of the probability distributions using 2-sample K-S tests revealed several interesting results. The most common gaze change from the left or right monitors was to the middle monitor, and these distributions were not significantly different from each other ($p = 0.675$). It was surprising that this change occurred more often than switches between the maps/monitors. Subjects were more likely to look from the left or the right monitor to the maps than from the middle monitor to the maps (Kruskal-Wallis, $p < 0.001$). Considering the lack of triangulation information provided by the end-effector camera (middle monitor) versus the fixed cameras, perhaps this is to be expected. There were no significant differences between the subjects' likelihoods of looking from the map to any of the monitors.

Table 4.9 compares the gaze transition probability matrices for high (above 20) and low scorers on the PTA. The highlighted cells show where there were significant differences between the distributions: switches from left-to-right ($p = 0.022$), middle-to-right ($p = 0.028$), middle-to-map ($p < 0.001$), map-to-left ($p = 0.002$), and paper-to-middle ($p = 0.001$). Only one of the distributions for high scoring subjects was significantly different from normal: transitions from the left monitor to the right. For low scoring subjects, transitions from left to right, middle to right, right to left, and map to left were significantly different from normal.

Table 4.9 - Gaze Transition Probabilities; High (left) & Low (right) PTA Scorers

	Left	Middle	Right	Maps
Left		0.546	0.082	0.371
Middle	0.340		0.450	0.210
Right	0.093	0.554		0.353
Maps	0.304	0.342	0.353	

	Left	Middle	Right	Maps
Left		0.543	0.044	0.412
Middle	0.339		0.391	0.270
Right	0.083	0.538		0.379
Maps	0.361	0.347	0.292	

There were gaze behavior differences between high and low PTA scoring subjects. Low scorers were more likely to look from a monitor back to the map than high scorers. They were less likely to switch from the left to the right, but their likelihood of switching from right to left was not significantly different from high scorers. While high scorers did not show significant differences between their probabilities of switching from the maps to any of the monitors, low scorers were less likely to switch from the map to the right monitor. However, these behavior differences may have been influenced by the way that the cameras were set up in order to monitor the effect of camera/control-frame disparity. The analysis should be repeated with a study that uses a more realistic camera setup.

4.4.5 Other Primary Operator Effects: Post-Test Questionnaire Results

Subjects were asked to report in the post-test questionnaire whether they flipped the paper maps of the environment upside down when they were using cameras 2 and 3. This would have removed the ~180° disparity between the map- and camera-frames. The technique was not suggested to the subjects, but was not discouraged.

As one might expect, the 3 subjects who reported flipping their maps under high disparity had lower PTA scores than the rest of the population (Kruskal-Wallis test, $p = 0.039$). Under the high-disparity condition, Kruskal-Wallis tests found that these subjects (Group 1 in Figure 4.13) had longer trial times (Figure 4.13a, $p = 0.017$), a higher number of continuous movements ($p = 0.050$), shorter movement durations (Figure 4.13b, $p = 0.050$), more changes in direction (Figure 4.13c, $p = 0.050$), and larger path errors (Figure 4.13d, $p = 0.039$).

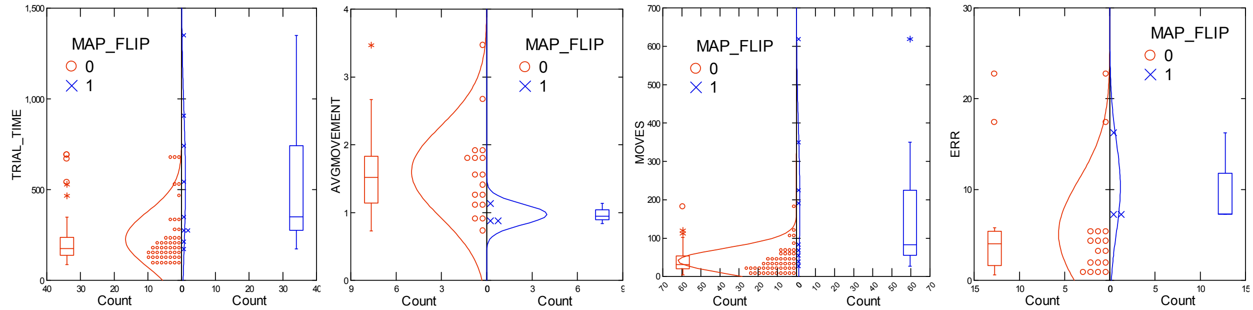

Figure 4.13 - Effect of Map Orientation with High Disparity Trials
(a) Time, (b) Avg. Move Duration, (c) Changes in Direction, and (d) Path Error by Map Flip Group

This strategy may have helped low scorers interpret high disparity camera views better, but their performance was still lower than that of the other subjects'.

4.4.6 Secondary Operator Spatial Ability Effects

Our fourth hypothesis was that subjects with higher SO and SV skills would perform better than the other subjects as a secondary operator observing telerobotic tasks. Mixed regression analysis finds that subjects made more correct detections (Figure 4.14a, $p < 0.001$), and fewer false alarms (Figure 4.14b, $p = 0.005$) and misses (Figure 4.14c, $p < 0.001$) as they progressed through the first 3 lessons. However, these measures did not significantly relate to SO and SV test scores.

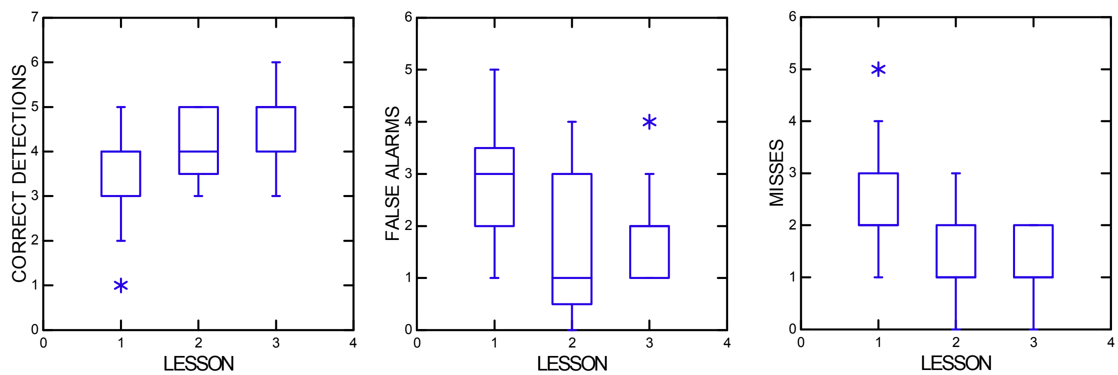

Figure 4.14 - Effect of Learning on (a) Detections, (b) False Alarms, (c) Misses

The only metric that did relate to spatial ability scores was whether the subject detected the problem before it had occurred. In the context of ISS operations, stopping the arm prior to a clearance violation or singularity is critical to avoid potential collisions or other problems. Subjects with high PTA scores had a higher percentage of timely correct detections (hits) during Lesson 3 than low scorers (Figure 4.16c, $p = 0.040$).

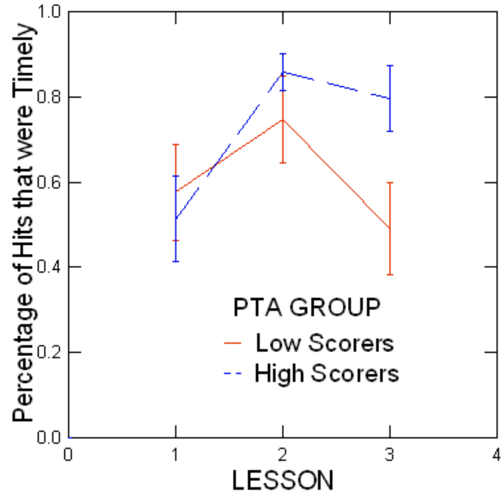

Figure 4.15 - Effect of PTA Score on Timeliness of Problem Detection

The subjects' total payoff scores ranged from \$2 - \$8. It is notable that all of the bonuses fell within a small range and all of the payments were positive. The bonuses were not normally distributed; the 7 subjects who scored higher than \$5 (Group 1 in Figure 4.16) had significantly higher PSVT scores than the other subjects (Figure 4.16a, Kruskal-Wallis, p = 0.043). They also had a higher number of hits during Lesson 3 (Figure 4.16b, Kruskal-Wallis, p = 0.019).

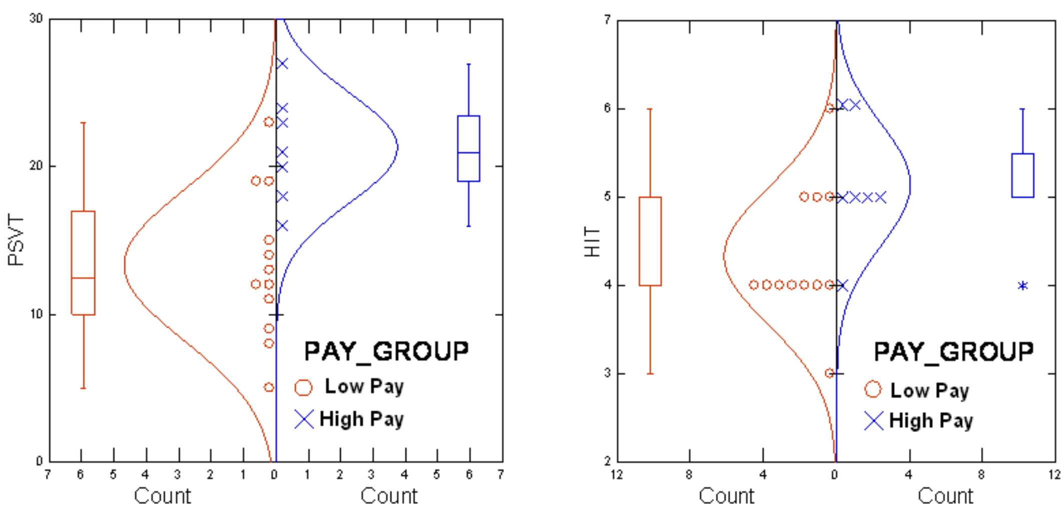

Figure 4.16 - Effect of Learning throughout the Secondary Operator Trials
PSVT Scores (left) and Lesson 3 Hits by Payment Group (right)

4.4.7 Secondary Operator Payoff Effects and ROC Curves

Our fifth hypothesis was that a secondary operator's probability of a correct detection or false alarm could be moved along their ROC curve by changing the payoff rule. We analyzed the signal detection performance of the two subject groups (control and payoff change) in terms of their overall performance, as well as looking at their performance with each problem type separately. We anticipated two effects: an improvement between lessons 3 and 4 due to learning, and – in the payoff change group – a leftward shift along the ROC curve, because the penalty for false alarms was doubled (from $0.25 to $0.50).

Overall performance for the control and payoff change subject groups are shown in Figure 4.17. Theoretical ROC curves are superimposed for each lesson. The figure shows that both groups had high performance and improved (more correct detections and fewer false alarms) between Lessons 3 and 4 (Kruskal-Wallis, correct detection $p = 0.023$, false alarm $p = 0.015$). Additionally, both groups apparently jumped to a new curve between lessons, suggesting that the signal to noise ratio of the detection process (see Sect. 2.4) had improved as a result of experience. There were no statistical differences in correct detection or false alarm rates between subject groups, but there was a significant cross-effect (payment group * lesson) on correct detection rate ($p = 0.027$).

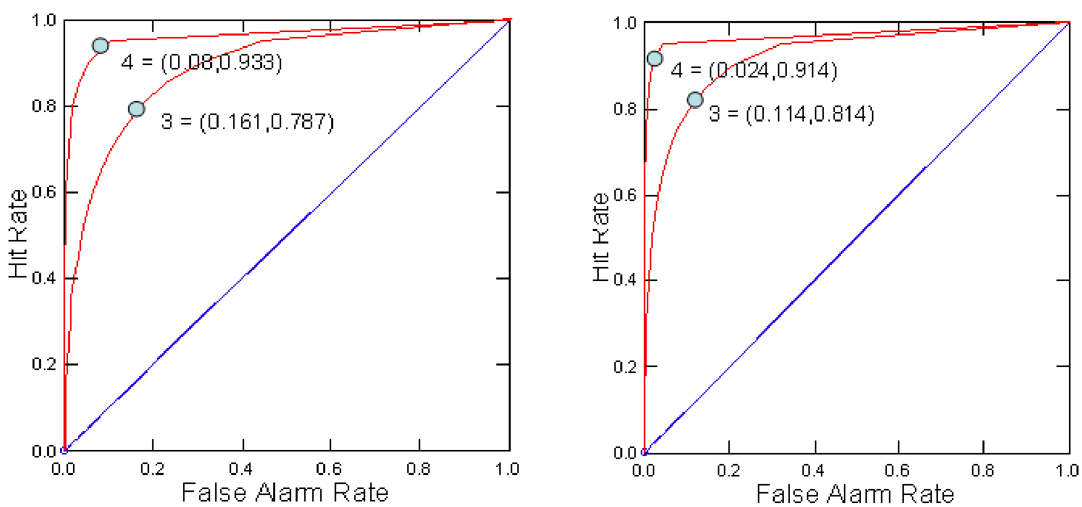

Figure 4.17 - Lesson 3 & 4 ROC Curves without (left) and with (right) Pay Change

During the clearance violation trials, the control (Figure 4.18a) and pay change subjects (Figure 4.18b) both changed their strategy between lessons, which is reflected by a curve change; there were no significant differences between groups with respect to correct detection or false alarm rates. This was also true for the unexpected motion trials (Figure 4.18c and d).

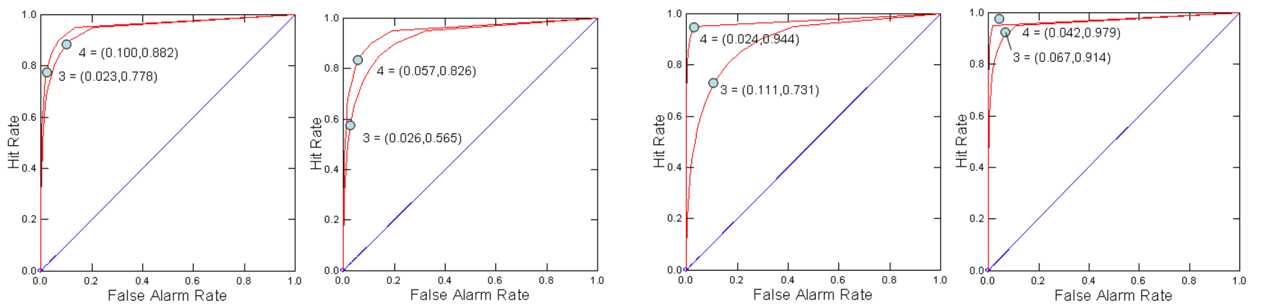

Figure 4.18 - Clearance Violation and Unexpected Motion ROC curves
Clearance Violation (a) Control, (b) Pay Change; Unexpected Motion (c) Control, (d) Pay Change

During the singularity trials, the control group (Figure 4.19a) changed strategies (and therefore moved to a different curve) between the lessons. During lesson 4, their correct detection ($p < 0.001$) and false alarm rates ($p < 0.001$) were higher than lesson 3. The payoff change subjects (Figure 4.19b) had a lower correct detection rate ($p = 0.011$) during lesson 4 than lesson 3. There were no statistical differences in correct detection or false alarm rates between groups.

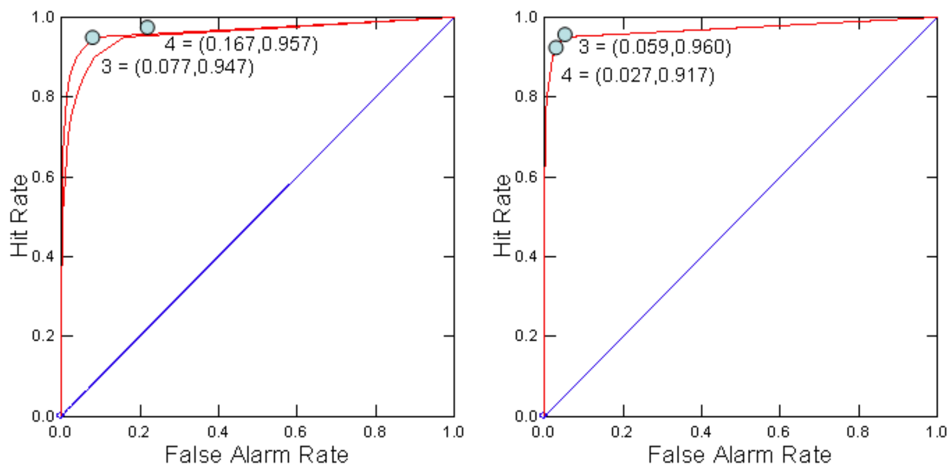

Figure 4.19 - Singularity ROC without (left) and with (right) Pay Change

In summary, subjects' performance improved as the lessons progressed, but payoff manipulations had inconsistent effects. This is further discussed in Section 4.5.3.

4.4.8 Primary and Secondary Operator Overall Performance

Our final hypothesis was that the worst performers on the primary operator tasks would also be the worst performers on the secondary operator tasks. However, the experiment showed that performance on primary operator tasks does not necessarily predict performance on secondary operator tasks.

Friedman analysis of the ranked sums of performance scores (see similar analysis in Section 3.5.1) suggested that some subjects consistently had the best (or worst) performance across several measures (trial completion time, percentage of time spent moving, and path error). Kruskal-Wallis tests showed that the 5 subjects with the lowest performance on the final primary operator trial had significantly lower BMC ($p = 0.048$), MRT ($p = 0.028$), and PTA ($p = 0.016$) scores than the other subjects (as expected). However, these subjects' performance was not significantly different from that of the rest of the subjects on the secondary trials

4.4.9 Other Secondary Operator Effects

Prior experience with the arm (resulting from participation in Experiment 1) did not have a significant effect on secondary operator performance. In addition, Kruskal-Wallis tests showed that the 7 subjects with perfect detection scores in Lesson 4 were not all at the same experience level or in the same pay change group and did not have significantly different MRT, PSVT, or PTA test scores from those of the other subjects.

About 1/3 of the subjects reported that singularities were the hardest type of problem to identify, and the rest chose clearance violations. However, there were no differences in total payment or timely hit percentage between the two groups and they did not have statistically different MRT, PSVT, or PTA scores.

4.4.10 Effect of Learning Strategies for Understanding the Environment

Experiment 1 inspired investigation via the Experiment 2 questionnaire of how subjects gained their understanding of the environment. Responses on the post-test questionnaire indicated that some subjects attempted to "memorize the layout of the environment during [the PowerPoint training]", while others chose to "wait and learn it as [they] went through the tasks". \

Subjects who tried to memorize the environment during the PowerPoint training (Group 0 in Figure 4.20) had shorter trial times (Figure 4.20a, $p = 0.001$), longer average movements (Figure 4.20b, $p = 0.024$), fewer continuous movements (Figure 4.20c, $p = 0.003$), and spent a higher percentage of their time spent moving (Figure 4.20d, $p = 0.009$).

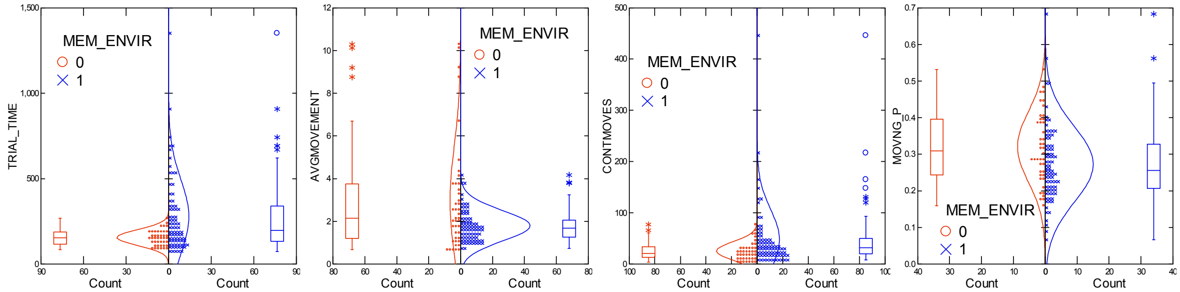

Figure 4.20 - Effect of Method for Learning the Environment
(a) Trial Time, (b) Avg. Movement Duration, (c) Continuous Moves, and (d) Moving Percentage

It is not surprising that careful study of the environment during the orientation later affected performance, but the relationship may not be that simple. Those who reported that they tried to memorize the environment during the PowerPoint training also had significantly higher PTA scores (Kruskal-Wallis, p = 0.013) than the other subjects. In addition, subjects with PTA scores above 20 spent a larger percentage of their total trial time than the others studying the map before beginning each trial (p = 0.004). It is possible that the lower scoring subjects were unable to gain an adequate understanding of the environment from studying the pictures and maps and reading the text provided in the PowerPoint training, and therefore truly needed to have "hands-on" training with the environment in order to understand it as well as their peers. This knowledge could be very important for robotics training; emphasis on map studying during NASA training may not be helpful for astronauts with low PT abilities.

The subjects were asked the same question about their strategy for learning the environment after the secondary operator trials. Several of those who originally carefully studied the orientation switched methods. It is likely that they believed their knowledge from the first portion of the experiment would be sufficient. There were no significant secondary operator performance differences between the subjects who still chose to study carefully during the orientation and those who did not.

4.5 Discussion

4.5.1 Predicting Performance

In this laboratory experiment, using relatively naïve subjects in the early phases of training, we found that primary and secondary operator performance correlated significantly with many measures of spatial and manual control ability even though primary and secondary operator overall performance was not correlated.

It should be noted that these results describe performance of laboratory subjects early in telerobotic training; the effects may be different in real-world telerobotics training with more highly trained subjects. Since NASA astronaut trainees are scored using qualitative measures, rather that the quantitative metrics, we could not directly compare performance in early NASA GRT with the performance of our subjects.

4.5.2 Effect of Experience in Prior Experiments

Returning subjects had significantly higher BMC scores than naïve subjects, which indicates that there was some effect of past experience with the task. However, when given new tasks, their overall performance did not differ significantly from the new subjects. It is possible that this result could be related to the time gap between the two experiments (2-5 months), but their improved BMC scores indicate that they retained some of their training.

4.5.3 Secondary Operator Payoff System and Effects

A bonus payment system was used to encourage performance during the secondary operator trials, and to establish a known “payoff rule”. The potential reward had to be large enough to be meaningful (approximately 1 extra hour's pay), while the penalty for missed detections had to be reasonable given the subjects' modest training level. For real world telerobotic operations on ISS, the “payoff rule” is obviously much different. On the ISS, missed detections can injure an EVA astronaut or cause a module to decompress, and impact an astronaut’s career prospects. To reflect the realities of on-orbit operations, a 1:5 positive-to-negative payment ratio for correct and missed detections was originally considered for this experiment. However, astronauts undergo hundreds of hours of training and the MIT subjects had only a couple hours of experience. A more generous 1:1 correct detection/missed detection rule was therefore adopted for this experiment.

The payoff rule for false alarms was also carefully considered. On the ISS, false alarms are preferable to missed detections, but they slow down progress and are therefore also undesirable. A false alarm penalty was therefore chosen that was significantly less than that for missed detections (1:2 ratio). This penalty was later doubled for half of the subject population in an attempt to manipulate the subject’s detection threshold.

Subjects with high PSVT scores may not have simply been better at detecting problems, but may have also been more adept at manipulating their performance to maximize their reward (i.e. since false alarms counted half as much as a missed detection, they may have decided to take a guess instead of missing an event). This ability may not be directly related PT, but SpA is a component of general intelligence.

Attempts to modify the subjects' performance with a payoff rule change to move the operating point on the ROC curve did not yield consistent results. The post-test questionnaire indicated that at best the reward system may have only been a secondary motivational factor; almost all of the subjects stated that they did not change their behavior for the last lesson, either because they were already doing their best or because they believed they had mastered the task of avoiding false alarms. Only one of the queried subjects reported consciously attempting to improve for the last lesson under the changed payoff rule.

4.5.4 Correlation between PSVT and PTA scores

Scores on the PSVT and PTA were not correlated in Experiment 1, but were correlated in Experiment 2. Performance measures in the first experiment generally correlated to PSVT, but not PTA. In Experiment 2, performance generally individually correlated with both PSVT and with PTA, but the PTA results were more significant.

5 Experiment 3 (Pilot Study)

5.1 Objectives

A pilot experiment was developed to address some questions raised by Experiments 1 and 2 regarding operator camera selection skills. Camera selection skills are emphasized in NASA GRT training, but including a study of camera selection in Experiments 1 and 2 would have sacrificed our ability to study the effect of camera/control-frame disparity and complicated performance comparisons. The experiment design and some preliminary data are included in the following sections.

The objectives of this experiment were:

1. To investigate the effect of spatial abilities on performance in setting up cameras to view a telerobotic task
2. To assist NASA trainers in tailoring training to optimize learning and performance during robotics training

5.2 Hypotheses

Given the objectives outlined above, we hypothesized that:

- Subjects with better spatial orientation and spatial visualization skills would select the correct camera set more quickly and more often
- Subjects with better spatial orientation and spatial visualization skills would be better at correctly identifying potential clearance issues

5.3 Methods

5.3.1 Differences in MVL DST Environment

The virtual environment consisted of the same BORIS environment used in Experiment 1 (Figure 3.1) and the primary operator portion of Experiment 2. Instead of the target box used in Experiment 1, free-floating grapple targets (the orange square visible in Figure 5.1) were utilized. The arm was set in a fixed position for each trial instead of being maneuverable.

The cameras included the same four room cameras as in Experiment 1, but Camera 3 (located in the aft-starboard corner) was raised to 13.75 m above the floor and rolled +90°. A window view from the forward wall replaced the End-Effector camera as the fifth camera option. Instead of being stationary as in Experiments 1 and 2, all of the cameras except for the window view were able to pan through a 90° range in increments of 22.5°. Since Camera 3 was rolled 90°, it therefore appeared to tilt instead of pan. The window view was completely stationary.

5.3.2 Task

Subjects were given a specific scenario (start point of the arm and location of the free-floating target) and were asked to select the camera views that would be most useful for accomplishing the trial. Subjects were given detailed instructions for how to select camera views:

- **<u>Left Monitor: "Big Picture" View</u>**: Select a camera that will show as much of the environment as possible, making the arm and target visible throughout the trial.
- **<u>Middle Monitor: Clearance View</u>**: Determine what could cause a clearance violation and select an orthogonal view to monitor the distance between that object and the arm.
- **<u>Right Monitor: Task View</u>**: Select a camera that will allow determination of the arm's distance from the target while grappling. This view should be orthogonal to the target

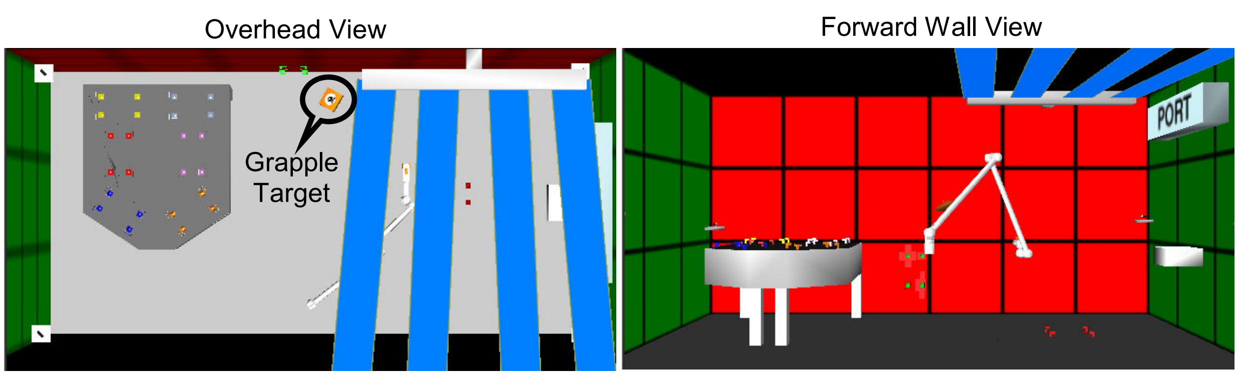

Figure 5.1 - Example of the Experiment 3 Task Setup Maps

At the beginning of each trial, the subjects were given paper maps (example in Figure 5.1) of the environment, showing the arm's position and the location of the grapple target. The subjects studied the maps before being prompted to enter their selections for initial camera views. The selected cameras were then displayed on the screen and the subjects could use keyboard controls[25] to modify the cameras if necessary before saving their selection. The subjects then indicated what clearance concern they had identified before moving on to the next trial.

5.3.3 Performance Metrics

At the end of each trial, several variables were recorded to a Summary Data File, characterizing the subject's performance. A summary of the recorded metrics is presented in Table 5.1. One Summary Data File was created for each lesson.

Table 5.1 - Experiment 3 Performance Metrics

Measures of performance	Description
Trial Time	The time that it took the subject to select the camera views
Initial Left, Middle, & Right Monitor Views	The initial selections made for the views
Preparation + Left, Middle, & Right Monitor Selection Times	The time that it took the subject to study the maps (preparation) and make their initial camera selections
Left, Middle, & Right Monitor Views	The final selections (camera and pan angle) for the views
Left, Middle, & Right Monitor Changes	The number of changes made (camera and pan angle) on each of the monitors
Clearance Issue	What the subject perceived to be the clearance issue that they needed to worry about
Overall Score[26]	A weighted combined metric computed from camera selections and the answer to the clearance issue question.

5.3.4 Subjects

For the pilot study, 4 male subjects were recruited from the MVL (demographics listed in Appendix P). All were right-handed and their ages ranged from 22 to 25. All but 1 had

[25] The F5, F6, and F7 keys allowed the subject to select a monitor to manipulate (left, middle, right, respectively). The 1, 2, 3, 4, and 5 keys allowed them to select a camera for that monitor (Cameras 1-4 + the window, respectively). The left and right arrow keys allowed them to pan the camera to the sides.

[26] For the weighted overall score, the Big Picture view was worth 1 point, the Task view was worth 1.5 points, the Clearance view was worth 2 points, and the question about what clearance situation they subject was concerned with was worth 0.25 points. This created a system where each possible combination of correct and incorrect answers resulted in a unique overall score.

experience with game or robotic controllers and had habit of playing video games. All subjects used a computer at least 5 hours a day.

5.3.5 Procedure

The experiment was conducted in the MIT MVL's VR Lab over one 2-hour session. Subjects were first given a Pre-Test Questionnaire (Appendix R with results in Appendix S) and 3 spatial ability tests (MRT, PSVT, and PTA). They then went through a PowerPoint presentation (Appendix T) which introduced them to the objectives of the experiment, the BORIS environment and arm. They then began the first of three 4-trial lessons.

During the second hour, subjects were asked to study the maps and determine which cameras they would like to start with (including an orientation angle for the Clearance view). Once their selected views appeared on screen, they could determine the accuracy of their selections and make changes as necessary before moving on to the next trial. At the end of the lessons, all subjects completed the Post-Test Questionnaire (Appendix U with results in Appendix V).

5.4 Results

5.4.1 Learning Effects

From the results of Experiment 2, we expected that the subjects would improve as the experiment progressed even if they did not receive performance feedback. There was great variation in performance among the subjects, which was expected. Generally, the subjects' trial times did not increase (Figure 5.2a), preparation times decreased (Figure 5.2b), and overall scores did not decrease (Figure 5.2c) over the lessons.

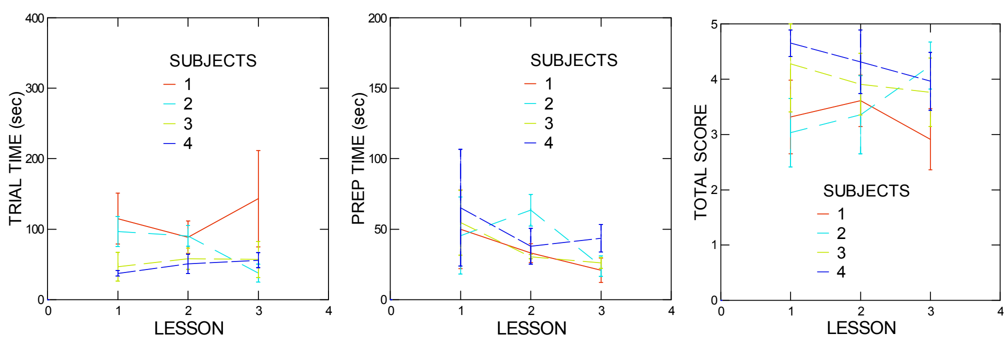

Figure 5.2 - Effect of Learning on Camera Selection
(a) Task Completion Time, (b) Preparation Time, (c) Total Score

5.4.2 Effect of Spatial Ability

We hypothesized that subjects with higher spatial ability scores would perform better at camera selection tasks. The results in Figure 5.3 show examples of the trends that the full study will look for. (No statistically significant results are claimed for these trends at this point).

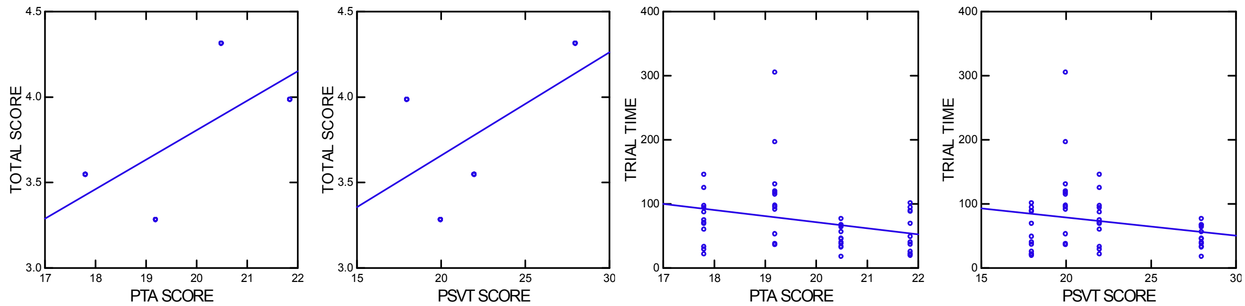

Figure 5.3 - Effect of Spatial Ability on Camera Selection
Total Score vs. (a) PTA and (b) PSVT; Trial Completion Time vs. (a) PTA and (b) PSVT

5.5 Discussion

The pilot study validated the overall experiment design. The full experiment will be conducted in the spring of 2009 with approximately 20 subjects.

The subjects in the study will have very little experience actually controlling the simulated arm. Although astronauts begin camera selection training very early in the GRT, they are simultaneously developing basic skills at manipulating the arm. This study should simulate camera selection performance during very early GRT lessons and will provide insights for conducting this introductory camera selection training. We considered having subjects return from Experiment 2 to participate in Experiment 3, but believe the extensive time gap between the studies (5-7 months) would not improve our ability to simulate skill levels during early GRT lessons.

6 Conclusions

The results of the two completed experiments described in this thesis supported their main hypotheses. In summary, the results of the primary operator studies were:

1. Performance on telerobotic tasks (defined by completion time, efficient navigation, clearance determination, and movement fluidity) is affected by specific spatial and bimanual control abilities
2. High camera- vs. control-frame disparities negatively affect some aspects of telerobotic performance (defined by changes in direction, path error, and completion time)
3. Perspective taking ability, as assessed by the PSVT and PTA, affects performance under high disparity conditions

The results of the secondary operator study were:

1. Overall performance as a secondary operator (defined by a combined metric of hits/misses/false alarms) and ability to have a timely reaction to a problem are affected by perspective taking ability (PSVT and PTA) scores.
2. Our attempt to manipulate subject performance by changing the cash bonus payoff rule for false alarms was unsuccessful. Arguably, we should have modified the missed detection penalty instead of false alarms, and/or designed the tasks with a lower incidence of problems to detect.

These studies were designed only to evaluate performance during early telerobotics training, such as during the first few lessons of the GRT. Table 6.1 outlines how low spatial or manual control abilities appear to relate to performance. While the data is not suited for predicting final telerobotics performance levels, the results gathered can be used to create skill profiles that could aid in developing individualized lesson-plan flows for beginner GRT trainees.

Our data indicates that during early training, performance in multiple areas is most affected by SpA in the early stages. Assisting low scorers (and therefore low performers) in catching up to their counterparts is critical. It is possible that some astronauts have difficulties later in training because they did not develop a good skill foundation in the beginning. Current GRT evaluation methods focus on how a trainee performs during each lesson. Subjects are given grades (plus, check, or minus) on up to a dozen relevant criteria, and an overall pass/fail decision is made for the lesson. Trainees cannot move on to the next lesson without passing the entire previous lesson. If a trainee receives minus scores within a lesson, their performance is monitored in the next lesson. If no improvement is noted, they may be encouraged to spend extra time practicing those skills. However, there is no direct monitoring of the effectiveness of these extra practice sessions. If low SpA scorers can be given tools and extra time to reach the same level as their higher scoring counterparts on all performance criterion before moving on to the next lesson, they may be more likely to stay at par throughout the training flow and not require remedial training.

Table 6.1 - Connections between Scores and Primary Operator Performance

Performance Characteristics	
BMC	▪ Percentage of time spent moving the arm ▪ Number of movements made, regardless of disparity
MRT	▪ Overall performance on a Fly-To a point task
PSVT	▪ Error from the shortest path to a target ▪ Ability to avoid clearance violations when a direct view is not available ▪ Ability to find the shortest path to the target under high disparity ▪ Align with the target without drifting when using the "wrong" control mode
PTA	▪ Time required to complete a Fly-To a point task ▪ Percentage of time spent moving the arm ▪ Error from the shortest path to a target ▪ Ability to avoid clearance violations when a direct view is not available ▪ Fluid arm movements (instead of starting and stopping) ▪ Ability to navigate the arm under high disparity ▪ Overall performance on a Fly-To a point task

Many measurements of primary operator performance correlate with scores on tests of perspective taking ability. Individual trainees, however, may struggle in only a few of these areas, or may have difficulty with all of them. Future initial robotics aptitude assessments should be developed to give a better idea of what training areas an astronaut may need extra help with, instead of just testing for general robotic manipulation ability. Extra lessons in these areas, or guidelines the astronauts can use for practicing on their own, could improve performance.

We also observed that learning strategies for understanding the environment (i.e. studying written instructions and pictures vs. getting hands-on experience) apparently impacted early performance. It may be useful to determine how much extra interaction time is required in order for those with poor PT skills to reach the same level as their peers; this extra time could be built into those astronauts' individual training flow.

If measures similar to those used in these experiments could be recorded during GRT and/or PDRS training, the subjective scoring system currently used by robotics instructors could be made more objective. Comparing uncorrelated performance measures[27] to the current subjective rankings would allow for the development of a quantitative definition of "passing" scores. An objective grading system would reduce the amount of variation in scoring between instructors and could improve the overall training experience.

The development of extra formal lessons or guidelines for practice sessions will require increased work from trainers, but will, one may hope, result in an improved training flow.

[27] For both experiments in this thesis, we sought to determine the effect of spatial ability on overall primary operator performance using multiple measures. However, we did not look for correlations between these measures. In order to develop an effective quantitative scoring system, the measures used to determine an overall score ideally should be statistically independent.

7 Suggestions for Future Work

This thesis continues the efforts begun by previous students to understand how spatial ability affects space teleoperation performance. While most of the original research aims were achieved, some were not and important new questions arose during the course of these studies.

- All of our experiments used fixed numbers of training sessions and trials, but astronauts are allowed to practice as much as required in order to pass each lesson. The logistics will be more complex, but designing a longer experiment where subjects train to proficiency may allow determination of how spatial ability affects required training time.
- These studies focused more on how steady state or average performance was affected by spatial ability rather than by learning rates. Further analysis of the data from Experiment 1 and the primary operator trials of Experiment 2 could reveal new insights on how people learn to perform telerobotic tasks.
- People learn at different rates and achieve different final performance levels. The difficulties encountered in developing the one-size-fits-all training programs for our experimental subjects highlighted the potential value of adopting personalized training for subjects. Matching teaching styles to learning styles is often important for astronauts who are struggling to develop the necessary skills. It could be useful to develop a few different styles of instruction (some using direct interaction and some not) and see if there is a link between spatial ability scores and the teaching style that works best.
- During GRT training, an entire lesson is devoted to the development of skills at controlling the arm in single joint mode. In this mode, the operator controls one arm joint at a time and must constantly be aware of how the rest of the arm will move in response. Successful operation in single joint mode requires an understanding of the arm's kinematics and visualization of its path in order to minimize the number of necessary movements. While the single joint tasks completed during early training (moving to a coordinate in the virtual environment) are different from those where single joint mode would be used in orbit (freeing the arm from a singularity or moving through a tight space), it could still be useful to predict how a student will perform during single joint lessons in the GRT. SV skills, as measured by the CC or paper folding tests, could be especially relevant.

- The results of the gaze analysis were likely influenced by the way that the cameras were set up (with 2 low or 2 high disparity views and the end-effector). Future experiments should repeat the study utilizing more realistic cameras (big picture, task, and clearance views, as in Experiment 3) to get a more accurate understanding of how subjects divide their attention during teleoperation tasks and whether this is affected by spatial abilities.
- Gaze tracking data was collected for the secondary operator portion of Experiment 2, but there was not adequate time to analyze it. Completing this preliminary study of how spatial ability affects gaze, and how that in turn affects performance may yield interesting results. Additionally, if future studies into gaze tracking are conducted, it could be useful to include a reaction test. Instead of simply judging a how long it takes for a subject to react to an image or sound, this test should be more like a video game and track reactions to changes in a virtual environment. It is possible that this test could be incorporated with a future version of the Bimanual Control Test.
- The secondary operator portion of Experiment 2 used varying task types and (when compared to the reward for correct detections) a low penalty for missed detections. The trials were kept relatively short to maintain the subjects' interest and level of performance. This task design may have made it more difficult to observe differences in performance. Additional studies may uncover new results by:
    - Using a single task type (environment and payload) for all of the trials
    - Making the trials longer in duration with more than one problem per trial
    - Assessing a larger penalty for missed detections

Other suggestions for future studies:

- Develop computerized pre-test and post-test questionnaires to make grading easier.
- Include a question as to whether subjects play a musical instrument (and which one) in a pre-test questionnaire if the task involves bi-manual control of the robotic arm.
- Develop a simulator feature so that the user can select whether or not to use three monitors (in the VR Lab) or display all three views within a single window (for use during debugging in the office/at home or for demos on laptops when not at the lab).

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9 Appendices

APPENDIX A - Experiment 1 Subject Basic Data[28]

Subj	Gender	Writing Hand	CC	MRT	PTA	PSVT	BMC
201	M	Right	30	13	23.352	24	27.86
202	F	Right	36	1	18.452	19	25.34
203	M	Right	40	15	25.061	13	4.25
204	M	Right	26	4	18.318	18	28.65
205	M	Right	34	9	21.248	23	25.96
206	M	Right	23	10	16.299	17	6.78
207	F	Left	28	4	18.238	19	26.97
208	F	Left	29	5	20.605	12	32.90
209	M	Right	10	-2	20.983	9	27.58
210	M	Right	33	8	21.779	23	4.68
211	M	Right	29	11	24.328	24	30.61
212	M	Right	28	5	18.695	16	23.94
213	F	Right	16	5	17.517	10	29.24
214	M	Right	33	2	17.533	10	23.22
215	M	Right	16	9	18.917	15	31.08
216	M	Right	31	10	20.515	11	37.68
217	M	Right	33	11	26.482	19	30.43
218	F	Right	37	10	28.096	14	29.24
219	F	Right	15	1	21.532	7	23.22
220	F	Right	11	6	15.826	12	31.08
221	M	Right	21	4	19.073	20	31.64
222	M	Left	13	6	21.506	13	28.03

[28] Subjects highlighted in gray were excluded from analysis

APPENDIX B - Experiment 1 Pre-Test Questionnaire

Gender: F M **Age**: _____

Right/Left handed: R L **Course #**: ______

Colorblind? Y N

1. **Do you have any experience with Virtual 3-D environments (e.g. 3-D games, CAD, 3-D graphic design, etc.)?**

(Yes No) (If "Yes," can you please describe this experience?)

2. **Do you have any experience with joysticks or game controllers? (e.g. computer games, video games, robotic manipulation)**

(Yes No) (If "Yes," can you please describe this experience?)

3. **How many hours per day do you use the computer?**
   ☐ 0 ☐ 1 – 3 ☐ 3 – 5 ☐ 5 – 7 ☐ More than 7

4. **What do you typically use the computer for? (Please check all that apply)**
   ☐ Email/word processing/web browsing ☐ Design (Graphical/Mechanical)
   ☐ Programming ☐ Gaming
   ☐ Other____

5. **Do you have / have you had the habit of playing video/computer games?**
   (Yes No) (If "No," go to question 10)

6. **What was your age when you started playing video/computer games?**
   ☐ < 5 ☐ 5 – 12 ☐ 12 – 18 ☐ 18- 25 ☐ > 25

7. **On average, how often (hours/week) did you play video/ computer games <u>when you played the most frequently</u>?**
   ☐ 1 – 3 ☐ 3 – 7 ☐ 7 –14 ☐ 14 – 28 ☐ > 28

   How many years ago was that?
   ☐ 0 ☐ 3 – 5 ☐ 5 – 10 ☐ 10 – 15 ☐ > 15

8. **On average, how often (hours/week) have you played video/computer games <u>in the past 3 years</u>?**
☐ 0 ☐ 1 – 3 ☐ 3 – 7 ☐ 7 –14 ☐ 14 – 28 ☐ > 28

9. **What kind of video/computer games do you play the most? (check as many as apply)**
☐ First person
☐ Role-playing/Strategy
☐ Arcade/Fighting (please specify: 2D 3D)
☐ Simulation (driving, flying)
☐ Sports (which? ______________________________)
☐ Other ______________

10. **Have you ever taken any spatial ability test before?**
(Yes No) (If "Yes", please list)
____
____
____

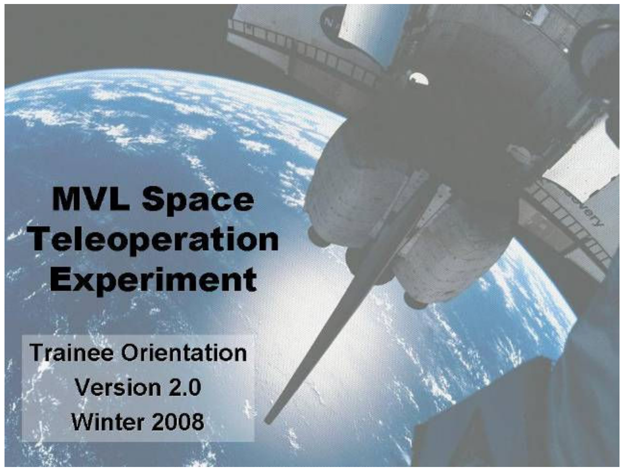
11. **Personal Measurements**
Height:
Leg Length: ____________
Arm Length:

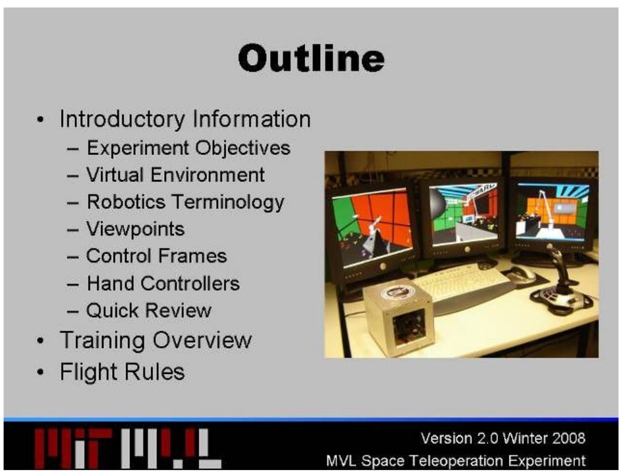
Thank you. You may hand this questionnaire back to the experimenter.

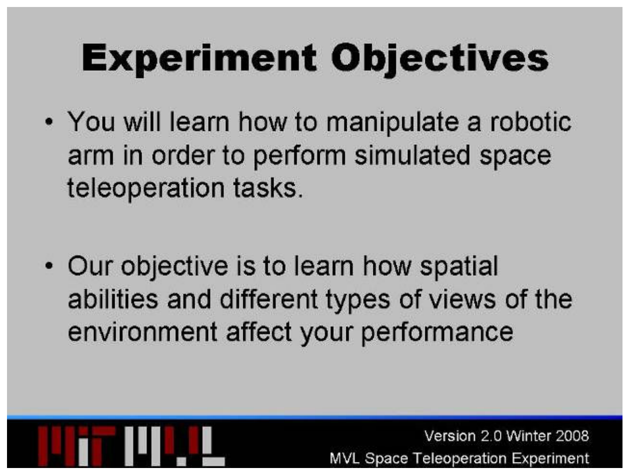
APPENDIX C - Experiment 1 Pre-Test Questionnaire Results

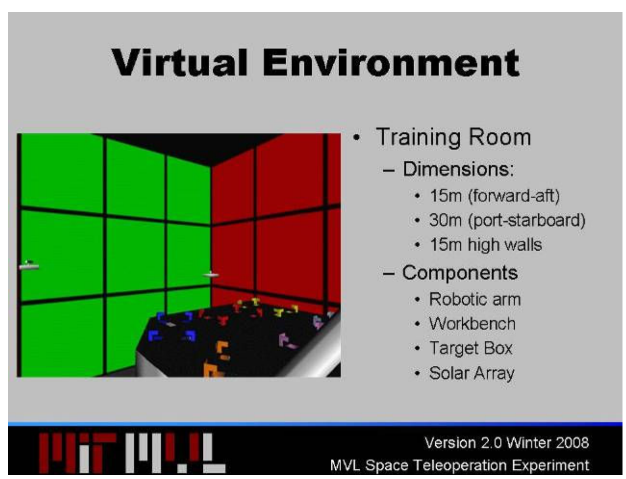
	3-D?	3-D Type	Contr Exp?	Exp Type	Comp Hours	Comp Usage	Game Habit?	Game Age	Game Hours	Game Years	Game Recent	Game Type	Prev SA?
201	Y	Design	Y	Comp	7+	E&D	Y	5-12	3-7	10-15	0	1st&RP&S	Y
202	N	N/A	Y	Video	7+	E&P	N						N
203	Y	G&C&D	Y	C & V	5-7	E&D&P&G	Y	5-12	7-14	5-10	0	1st Person	Y
204	Y	Games	Y	3	5-7	E&D&P&G	Y	5-12	7-14	10-15	0	1st&RP&A&S	Y
205	N	N/A	Y	3	3-5	E-mail	Y	12-18	1-3	> 15	0	Sim	N
206	Y	G & CAD	Y	Comp	5-7	E&P	Y	5-12	14-28	3-5	3-7	RP	N
207	Y	CAD	Y	Video	5-7	E&P	N						Y
208	Y	CAD	N	N/A	5-7	E&D	Y	5-12	3-7	5-10	0	Arcade	N
209	Y	Games	Y	C & V	3-5	E&G	Y	5-12	14-28	3-5	14-28	1st&RP&A	N
210	Y	CAD	Y	Video	5-7	E-mail	Y	5-12	3-7	> 15	0	RP	N
211	Y	CAD	N	N/A	1-3	E-mail	N						Y
212	Y	Design	Y	Comp	7+	E-mail	Y	> 25	1-3	3-5	0	Arcade&S	N
213	Y	CAD	N	N/A	7+	E-mail	N						Y
214	Y	N/A	Y	N/A	5-7	E-mail	N						N
215	Y	G & CAD	Y	C & V	3-5	E&P&G	Y	5-12	7-14	10-15	3-7	RP&Sports	N
216	Y	N/A	N	N/A	7+	E&P	Y	5-12	14-28	5-10	1-3	1st P&A&S	N
217	Y	CAD	Y	16	5-7	E-mail	Y	5-12	3-7	10-15	1-3	Sim	N
218	N	N/A	Y	Video	1-3	E-mail	N						N
219	Y	G & CAD	Y	C & V	5-7	E&P&G	Y	< 5	> 28	3-5	1-3	1st P&RP&A	N
220	Y	Design	Y	Video	7+	E&D&P	N						N
221	Y	Games	Y	Comp	7+	E-mail	Y	12-18	3-7	10-15	0	1st P&S&Sp	Y
222	N	N/A	Y	N/A	3-5	E&G	Y	18-25	3-7	3-5	1-3	1st P & RP	N

APPENDIX D - Experiment 1 Training



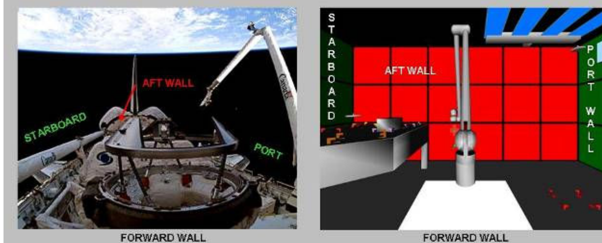






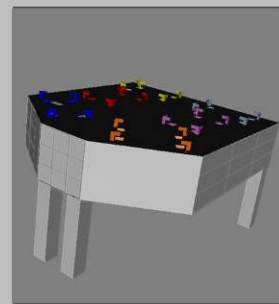
Virtual Environment Design

The walls are named "forward", "port", "starboard" and "aft" as though the environment were a space shuttle's payload bay. The environment was modeled after a NASA training tool for astronauts.



Version 2.0 Winter 2008
MVL Space Teleoperation Experiment

Environment Components

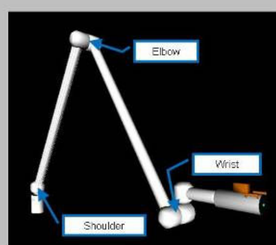


- Workbench
  - The workbench is a 6-sided table with 6 places (each shown as a different color in the image on the left) to put a target box.
  - It is located near the starboard wall.
- Solar Array
  - The solar array is made up of four blue solar panels and forms a ceiling over part of the environment.
  - It is mounted to the center of the aft wall.

Version 2.0 Winter 2008
MVL Space Teleoperation Experiment

Training Room Components

- Robotic Arm
  - Like a human arm, the robotic arm has three elements: a shoulder, an elbow, and a wrist.
  - It is 14 m long when fully extended.
  - The arm simulates the one used by astronauts onboard the space shuttle and the space station.



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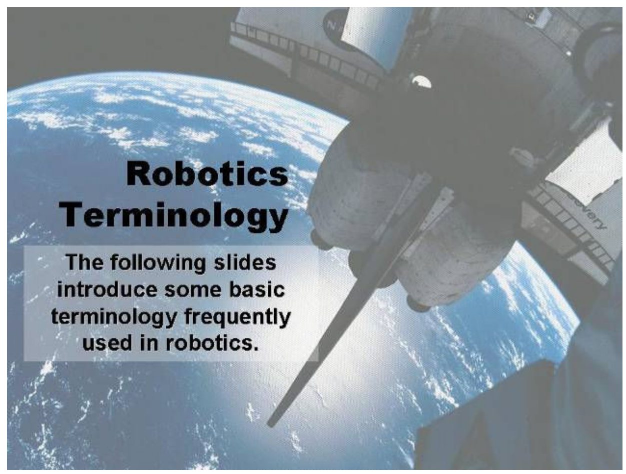
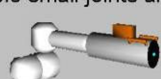
MVL Space Teleoperation Experiment



Robotics Terminology

- **Links** are the rigid bars that form the robotic arm.
- **Joints** allow two links to rotate with respect to one another.
- The **End-Effector** is the 'grasping finger' of the arm, made up of multiple small joints and links.



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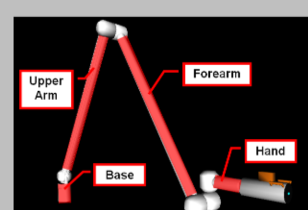
MVL Space Teleoperation Experiment

Robotics Terminology

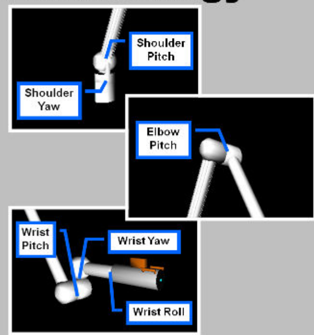
- The arm has:
  - **4 Links**



Experiment 2.1 Summer 2008
MVL Space Teleoperation Training

Robotics Terminology

- The arm has:
  - 4 Links
  - 6 Joints
    - The arm's joints allow it to move 6 ways in 3-D space
      - Left/right
      - Up/down
      - Forward/backward
      - Pitch
      - Yaw
      - Roll



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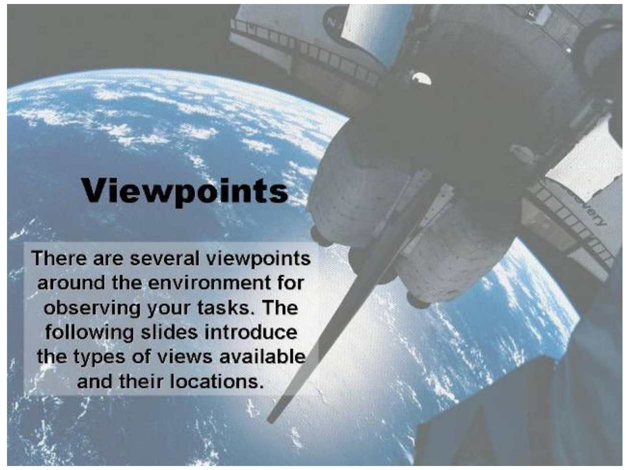

Viewpoints

- You will have three monitors giving you views of the environment
- There are 5 possible views:
  - Four views from numbered cameras inside the room (one is located in each corner)
  - One view from a camera placed on the end of the arm (the End-Effector Camera)
- The views will be selected for you

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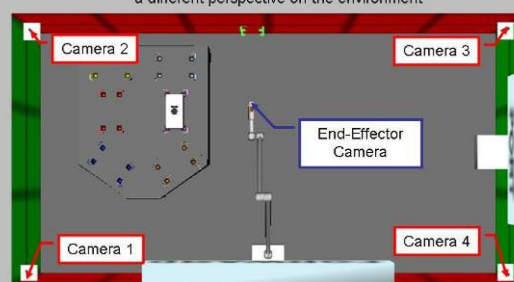
Viewpoints

Each of the 5 views (4 numbered cameras and the End-Effector Camera) gives a different perspective on the environment



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MVL Space Teleoperation Experiment

Viewpoints

The following slides show each of the viewpoints.

The views will be shown on the right. On the left, you can see where the camera or viewpoint is located within the environment.

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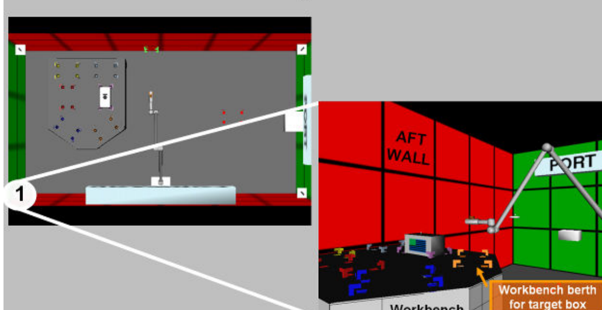
Viewpoints



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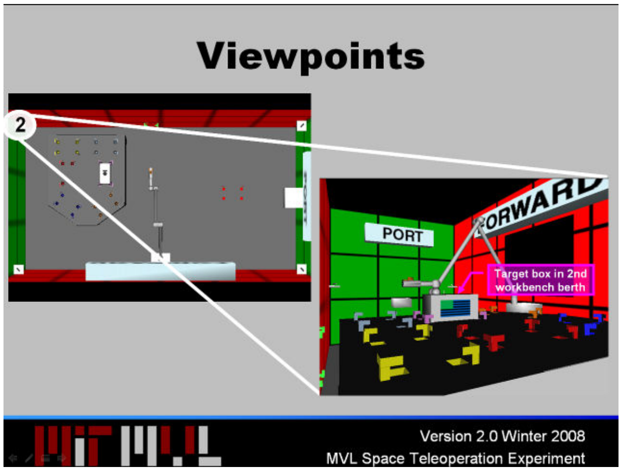
Viewpoints
2
PORT
FORWARD
Target box in 2nd workbench berth
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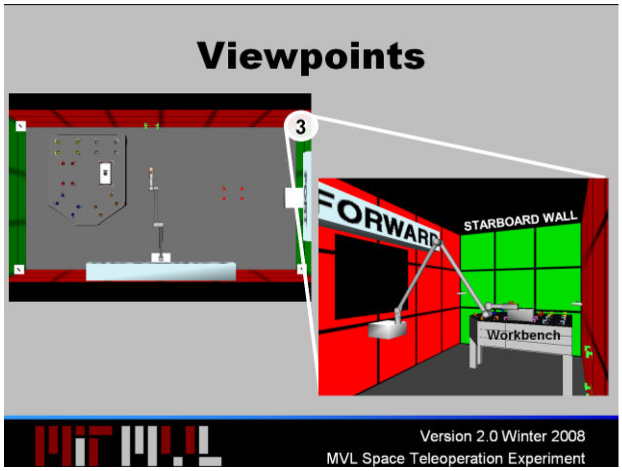
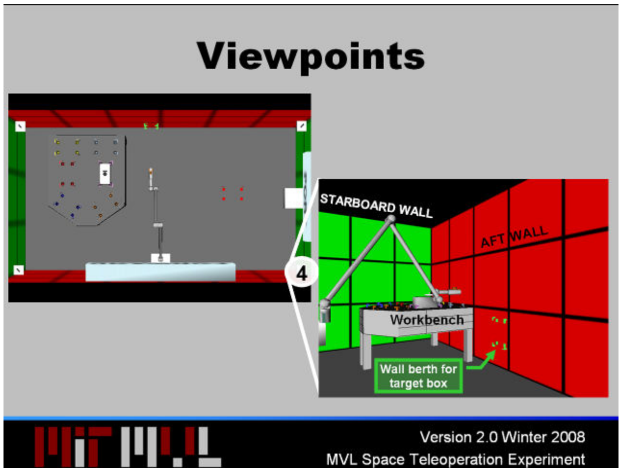

Viewpoints
3
FORWARD
STARBOARD WALL
Workbench
Version 2.0 Winter 2008
MVL Space Teleoperation Experiment


Viewpoints
4
STARBOARD WALL
AFT WALL
Workbench
Wall berth for target box
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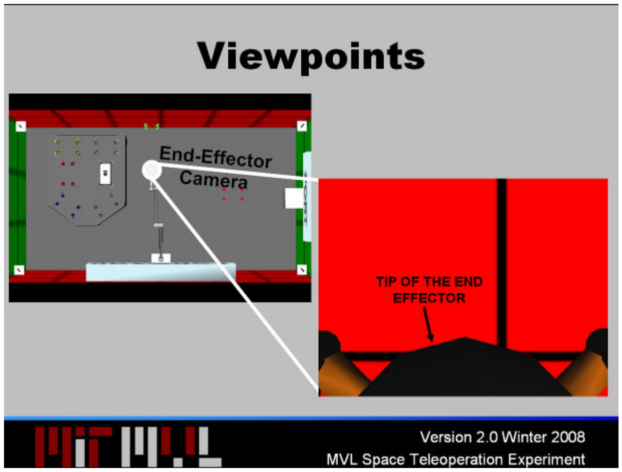
MVL Space Teleoperation Experiment


Viewpoints
End-Effector Camera
TIP OF THE END EFFECTOR
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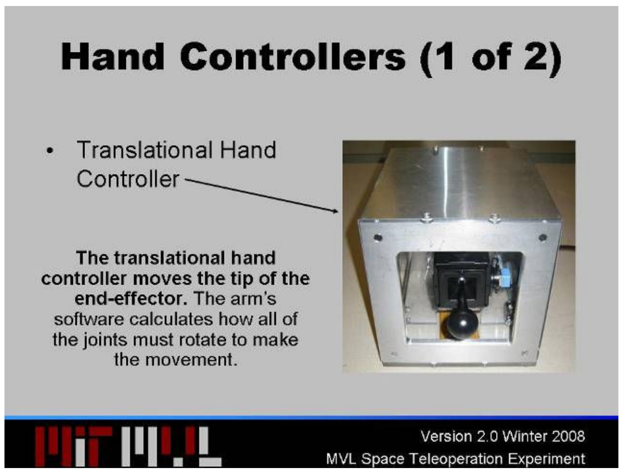
Hand Controllers
There are two hand controllers. The one on the left translates (moves forward/backward, left/right, or up/down) and the one on the right rotates the arm.


Hand Controllers (1 of 2)
• Translational Hand Controller
The translational hand controller moves the tip of the end-effector. The arm's software calculates how all of the joints must rotate to make the movement.
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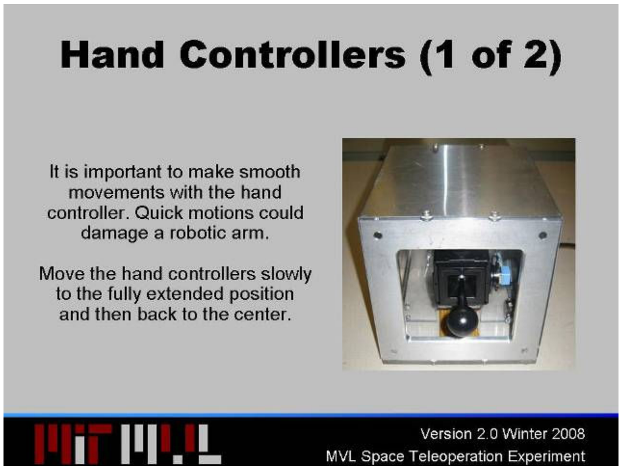
Hand Controllers (1 of 2)
It is important to make smooth movements with the hand controller. Quick motions could damage a robotic arm.
Move the hand controllers slowly to the fully extended position and then back to the center.
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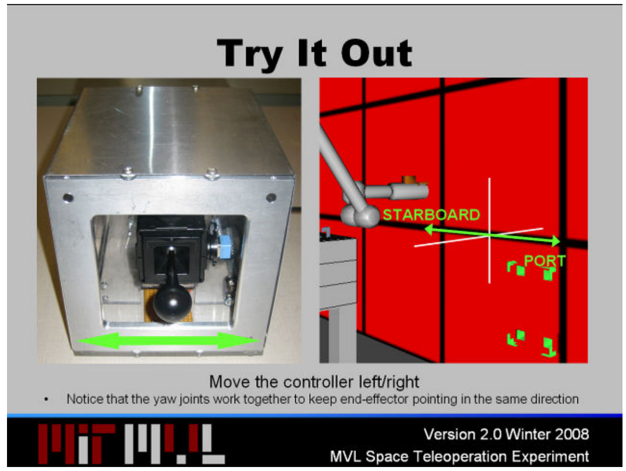
MVL Space Teleoperation Experiment


Try It Out
STARBOARD
PORT
Move the controller left/right
• Notice that the yaw joints work together to keep end-effector pointing in the same direction
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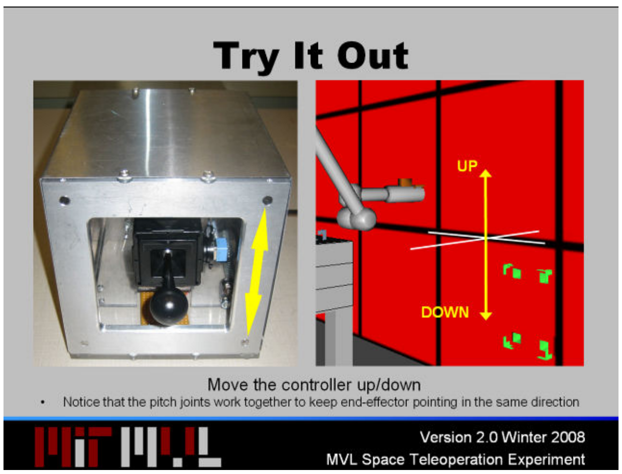
Try It Out
UP
DOWN
Move the controller up/down
• Notice that the pitch joints work together to keep end-effector pointing in the same direction
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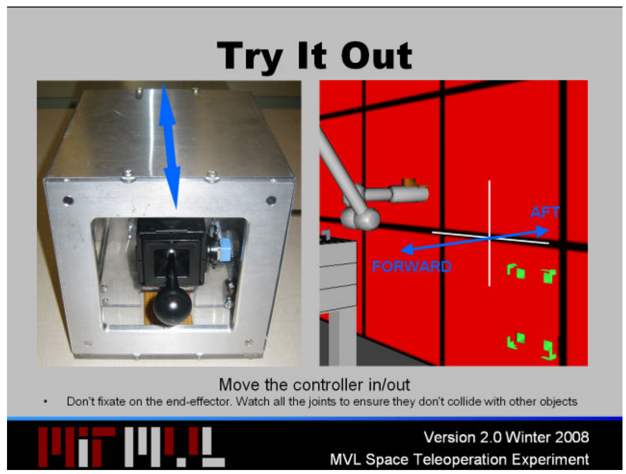
MVL Space Teleoperation Experiment


Try It Out
AFT
FORWARD
Move the controller in/out
• Don't fixate on the end-effector. Watch all the joints to ensure they don't collide with other objects
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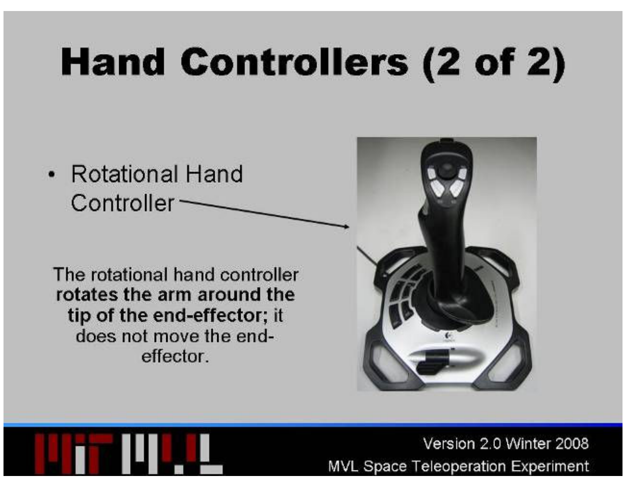
Hand Controllers (2 of 2)
• Rotational Hand Controller
The rotational hand controller rotates the arm around the tip of the end-effector; it does not move the end-effector.
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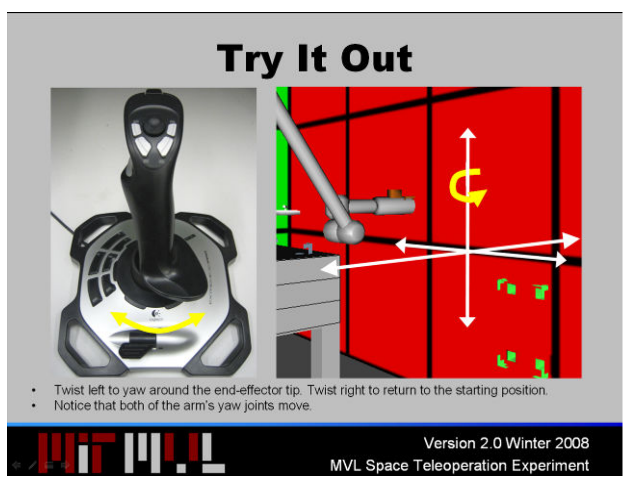
MVL Space Teleoperation Experiment


Try It Out
• Twist left to yaw around the end-effector tip. Twist right to return to the starting position.
• Notice that both of the arm's yaw joints move.
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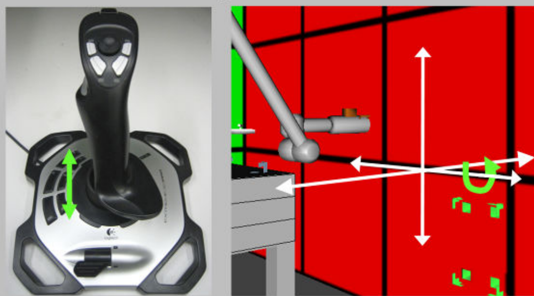
MVL Space Teleoperation Experiment

Try It Out



- Push forward to pitch around the end-effector tip; pull back to return to the starting position.
- Notice that all three of the arm's pitch joints move.

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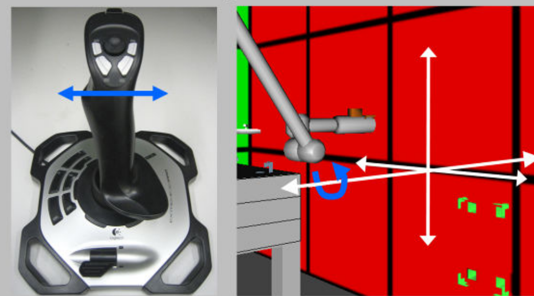
MVL Space Teleoperation Experiment

Try It Out



- Push right to roll around the end-effector tip; push left to return to the starting position.
- Notice that the end-effector roll joint is the only one that moves.

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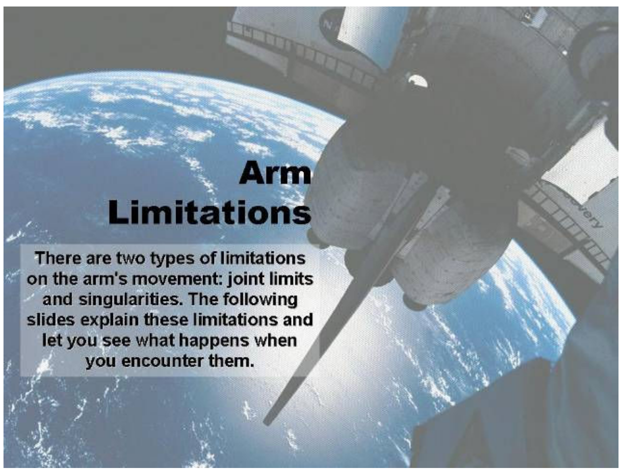
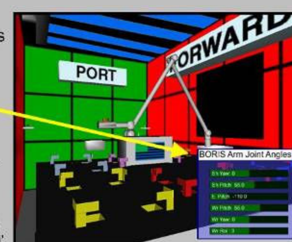


Arm Limitations

There are two types of limitations on the arm's movement: joint limits and singularities. The following slides explain these limitations and let you see what happens when you encounter them.

Joint Limits

- It's very important that you pay attention to what each of the arm's joints is doing, not just to where the end-effector is going.
  - The Joint Angle Info Display will help you do this.
    - Each bar shows:
      - What the joint's angle is
      - Where that angle falls within the joint's possible range of motion
    - Look at this display frequently while you are moving the arm.
    - You can move the display around the screen or hide it by pressing 'i'



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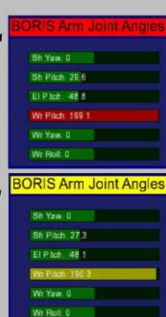
Joint Limits

- The Joint Angle Info Display will warn you about the arm's physical limits, which are called hardstops.
  - **Hardstops** are the limits on how far a joint can rotate.
  - If you see the Info Display turn red, you have encountered a hardstop.
    - This notice is also displayed on the screen: HARDSTOP
    - Move in reverse direction to free the arm
  - If you see the Info Display turn yellow, you are within 10° of a hardstop.
    - Look for this warning in order to avoid actually reaching the hardstop



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Try It Out – Joint Limits

- These steps to see what happens when you reach the wrist roll hardstop:
  - Press 'i' to bring up the Joint Angle Info Display
  - Push the Rotational Hand Controller right and hold it there
    - Watch what changes on the info display as you move
    - Notice what happens as you approach, and then encounter, the hardstop
  - Push the controller back to the left to return to the starting position (Wr Roll: 0)

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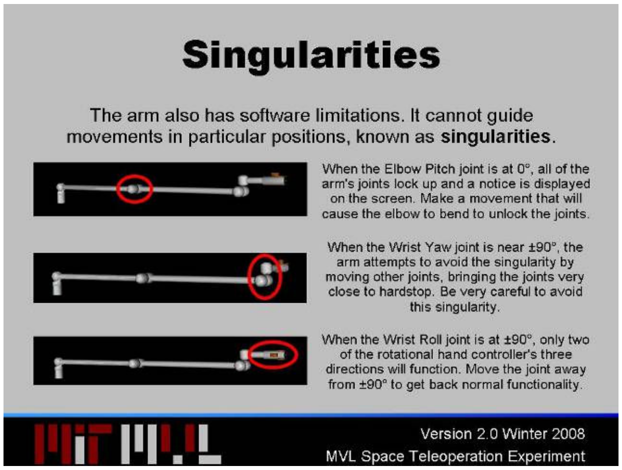
Singularities
The arm also has software limitations. It cannot guide movements in particular positions, known as singularities.
When the Elbow Pitch joint is at 0°, all of the arm's joints lock up and a notice is displayed on the screen. Make a movement that will cause the elbow to bend to unlock the joints.
When the Wrist Yaw joint is near ±90°, the arm attempts to avoid the singularity by moving other joints, bringing the joints very close to hardstop. Be very careful to avoid this singularity.
When the Wrist Roll joint is at ±90°, only two of the rotational hand controller's three directions will function. Move the joint away from ±90° to get back normal functionality.
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Try It Out – Singularities
• These steps will let you see what happens when you reach the elbow pitch singularity:
– Push the translational hand controller to the right and hold it there.
• Watch the arm move until it hits the singularity.
• Notice the warning displayed on the screen.
– Push the controller to the left to recover and return to the starting position.
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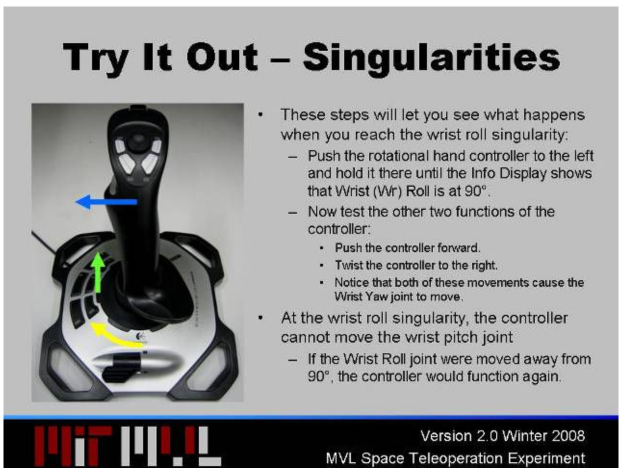
MVL Space Teleoperation Experiment


Try It Out – Singularities
• These steps will let you see what happens when you reach the wrist roll singularity:
– Push the rotational hand controller to the left and hold it there until the Info Display shows that Wrist (Wr) Roll is at 90°.
– Now test the other two functions of the controller:
• Push the controller forward.
• Twist the controller to the right.
• Notice that both of these movements cause the Wrist Yaw joint to move.
• At the wrist roll singularity, the controller cannot move the wrist pitch joint
– If the Wrist Roll joint were moved away from 90°, the controller would function again.
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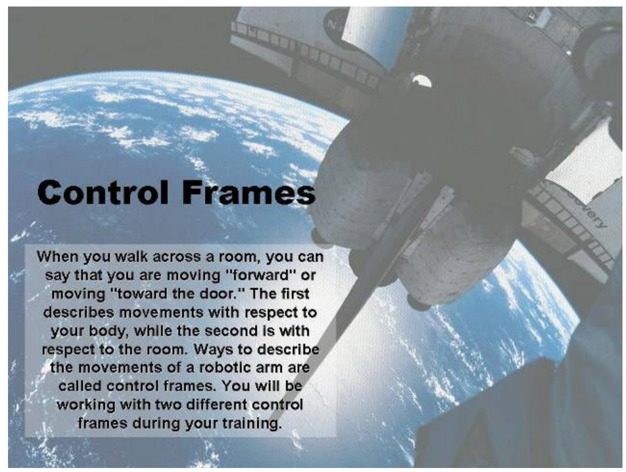
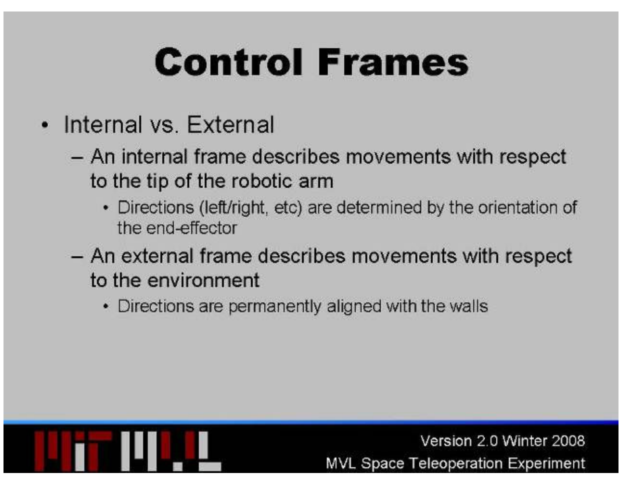

Control Frames
When you walk across a room, you can say that you are moving "forward" or moving "toward the door." The first describes movements with respect to your body, while the second is with respect to the room. Ways to describe the movements of a robotic arm are called control frames. You will be working with two different control frames during your training.


Control Frames
• Internal vs. External
– An internal frame describes movements with respect to the tip of the robotic arm
• Directions (left/right, etc) are determined by the orientation of the end-effector
– An external frame describes movements with respect to the environment
• Directions are permanently aligned with the walls
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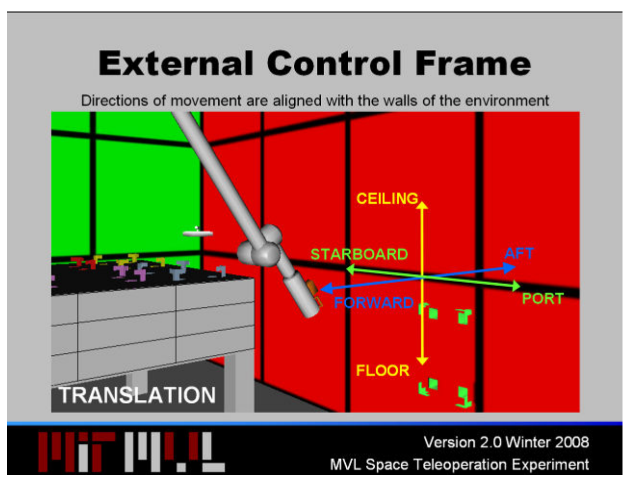
External Control Frame
Directions of movement are aligned with the walls of the environment
CEILING
STARBOARD
AFT
FORWARD
PORT
FLOOR
TRANSLATION
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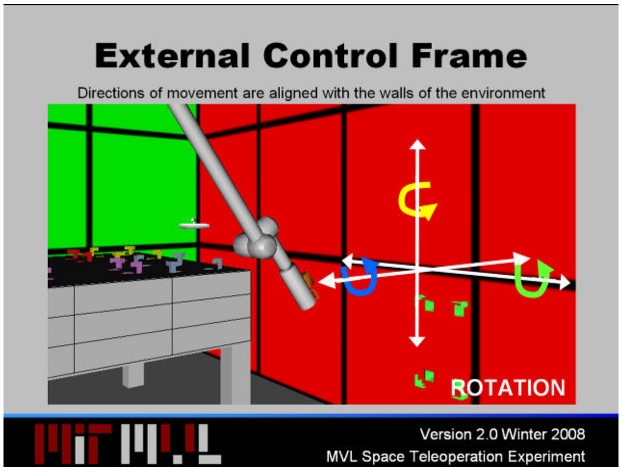
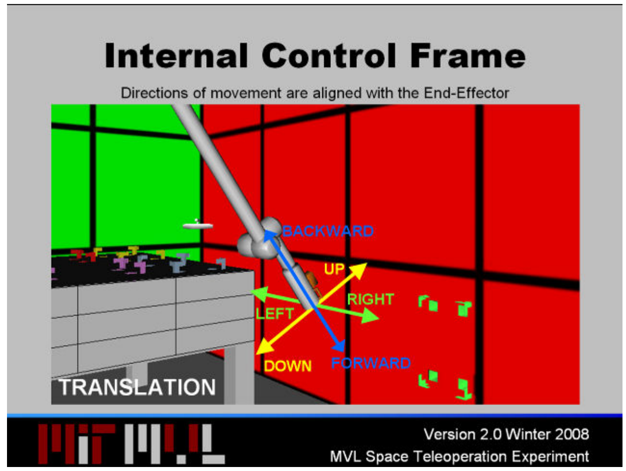
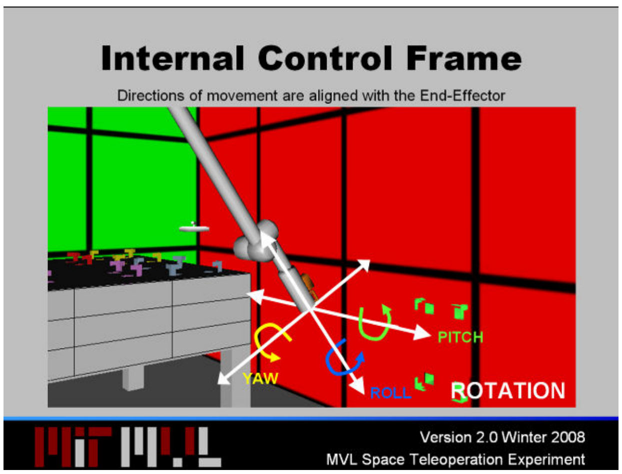
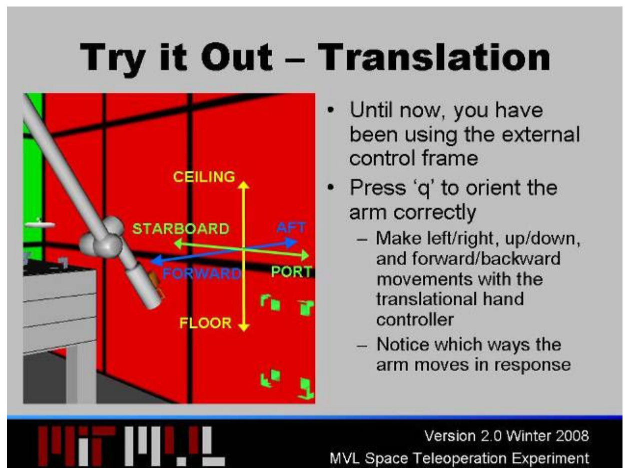
MVL Space Teleoperation Experiment


External Control Frame
Directions of movement are aligned with the walls of the environment
ROTATION
Version 2.0 Winter 2008
MVL Space Teleoperation Experiment


Internal Control Frame
Directions of movement are aligned with the End-Effector
BACKWARD
UP
RIGHT
LEFT
DOWN
FORWARD
TRANSLATION
Version 2.0 Winter 2008
MVL Space Teleoperation Experiment


Internal Control Frame
Directions of movement are aligned with the End-Effector
PITCH
YAW
ROLL
ROTATION
Version 2.0 Winter 2008
MVL Space Teleoperation Experiment


Try it Out – Translation
CEILING
STARBOARD
AFT
FORWARD
PORT
FLOOR
• Until now, you have been using the external control frame
• Press 'q' to orient the arm correctly
– Make left/right, up/down, and forward/backward movements with the translational hand controller
– Notice which ways the arm moves in response
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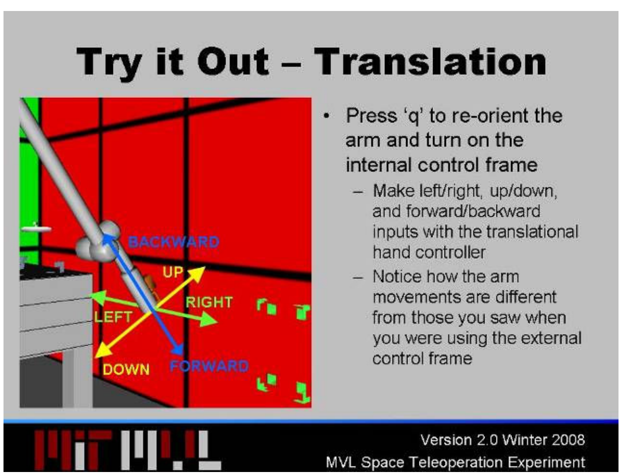
Try it Out – Translation
BACKWARD
UP
LEFT
RIGHT
DOWN
FORWARD
• Press 'q' to re-orient the arm and turn on the internal control frame
– Make left/right, up/down, and forward/backward inputs with the translational hand controller
– Notice how the arm movements are different from those you saw when you were using the external control frame
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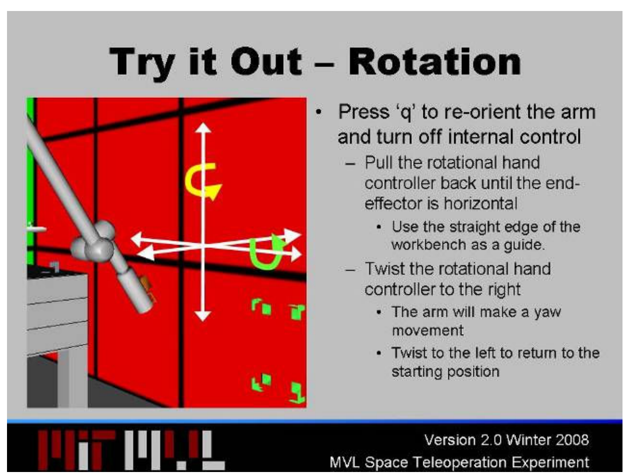
MVL Space Teleoperation Experiment


Try it Out – Rotation
• Press 'q' to re-orient the arm and turn off internal control
– Pull the rotational hand controller back until the end-effector is horizontal
• Use the straight edge of the workbench as a guide.
– Twist the rotational hand controller to the right
• The arm will make a yaw movement
• Twist to the left to return to the starting position
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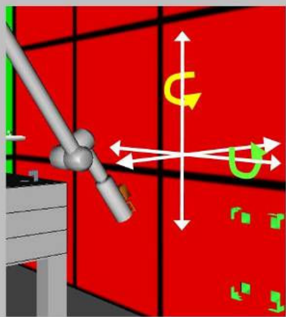
Try it Out – Rotation



- Push forward until the end-effector is vertical
  - Use the wall lines as a guide
- Twist the rotational hand controller to the right
  - Now the wrist roll joint will move
  - Keep in mind that as in the previous slide, the controller movements caused rotation about a single axis.
    - When using external control, rotations are linked to axes, not specific joints.

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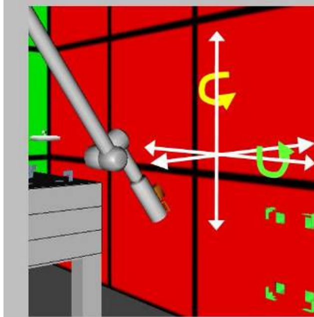
Try it Out – Rotation



- Twist the rotational controller to the left to return to the starting position.
- Pull backward until the end-effector is approximately halfway between horizontal and vertical (as in the image shown on the left)
- Twist the rotational hand controller to the right
  - Notice that the arm is rolling and yawing around the vertical axis because the arm is no longer perfectly aligned with any of the rotation axes.
  - To improve your control of the arm, always be aware of its orientation with respect to the rotation axes.

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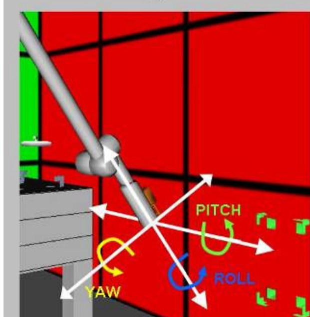
Try it Out – Rotation



- Press 'q' to re-orient the arm and turn on internal control mode
- Twist the rotational hand controller to the right
  - The arm will yaw about the tip of the end-effector
- Twist the controller to the left to return to the starting position
- Push the rotational hand controller forward until the end-effector is vertical
- Twist the rotational hand controller to the right
  - The arm will once again yaw.
  - In the internal control frame, rotation occurs around axes that are fixed with respect to the arm

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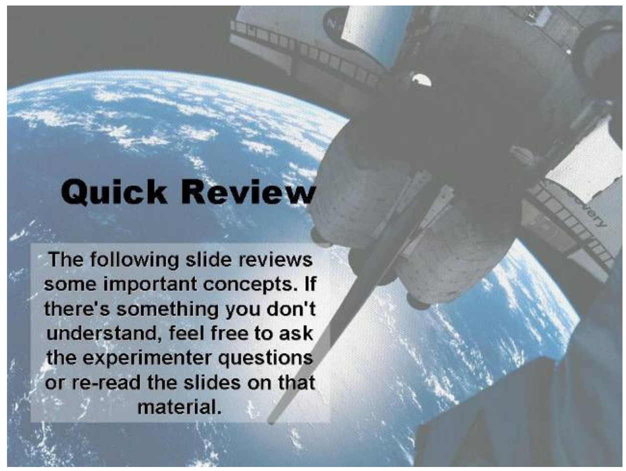

Review of Important Concepts

- Camera Viewpoints
  - The BORIS environment has **6 viewpoints**
    - 4 fixed views in the room
    - 1 fixed view found outside of the room
    - 1 mobile view on the arm
- Hand Controllers
  - Two kinds:
    - **Translational** (on your left)
    - **Rotational** (on your right)
- Arm Limitations
  - **Hardstops** are the limit on how far a joint can rotate.
  - Limitations in the arm's software cause three types of **singularities**.
- Control Frames
  - **Internal**: directions are relative to the end-effector
  - **External**: directions are relative to the room

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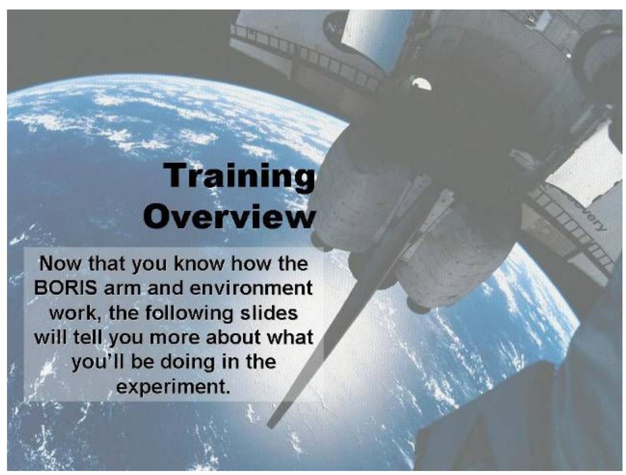

Training Overview

- Training Lessons
  - The lessons will allow you develop proficiency at a type of space teleoperation task. The following slides will describe this task in detail.
  - There are 3 lessons, and you will do 4 activities in each of them.
- Skills Test
  - After the 3 training lessons there will be a final skills test
  - The test will be made up of 4 activities from the training lessons.
  - Your score will be determined by:
    - How long it takes you to complete each activity
    - How efficiently you move the arm from the start point to the goal
    - How well you follow the flight rules, which will be described shortly

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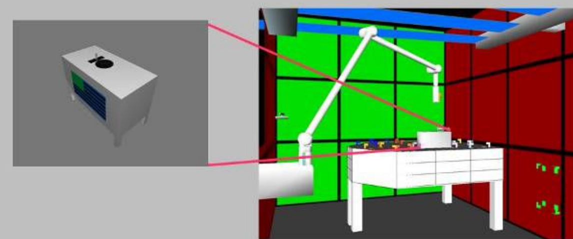
MVL Space Teleoperation Experiment

Training Task – Step 1

You will train on how to perform a Fly-To task. Move the arm **across the room** to the target box while avoiding obstacles.



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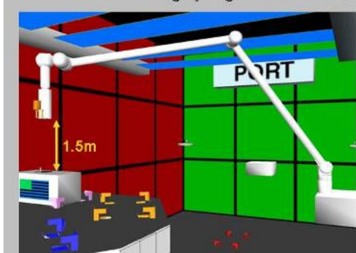
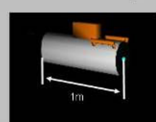
Training Task – Step 2

Move the end effector to a location **1.5 meters** above the target box and roughly align the end effector with the target



Hint: The last component of the end-effector is 1 m long; you can use this as a guide.



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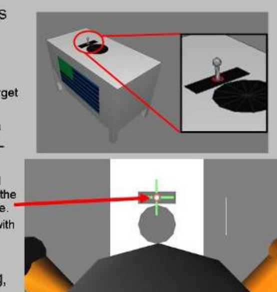
Training Task – Step 3

- When the end-effector is 1.5 meters above the target box, fine tune its alignment.
  - There are three tools to help you:
    1. A pitch & yaw alignment peg on the target
    2. A roll alignment box on the target
    3. Crosshairs on the end-effector camera
  - Follow these steps to align the end-effector with the target:
    1. Use pitch with up/down translation and yaw with right/left translation to center the tip of the alignment peg in the red circle.
    2. Use roll to align the green crosshairs with the box on the target.
- When you are happy with the end-effector's alignment and positioning, press **SPACE BAR** to end the task.



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Flight Rules

- Overall clearance limitation: 2 ft (0.6m) between the arm and all obstacles/walls
  - A warning will be shown on the screen when any part of the arm comes within this limit:

    Clearance Violation

  - Look for what has caused the clearance violation and move away to remove the warning.
- You must avoid collisions between the arm and obstacles/walls or with itself
  - If a collision occurs, the arm will bounce off of the object, and this warning will be displayed on the screen:

    COLLISION

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MVL Space Teleoperation Experiment

Flight Rules

- Work as quickly as you can without making more errors.
- There is no time limit for each activity, but you will be given a higher rating for better overall performance and speed.

Performance Ratings

1. Corps Applicant
   - You'll do better next time
2. Astronaut Candidate
   - You're showing improvement
3. Mission Specialist
   - You're certified for the shuttle
4. Flight Engineer
   - You're certified for the ISS
5. Lead Arm Operator
   - You're certified to lead the robotics team

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Things to Be Aware Of

Cameras
- Use your viewpoints, observe clearances, monitor the task.

Frames
- Think carefully about how to move the arm in each control frame.
- Internal control will be turned on for you when you must use it.

Joints
- Be aware of location of joint angle limits and arm singularities.

Rates (of movement)
- Slowing down the arm may give you better control.
  - Press 'v' to activate 'Vernier rate mode' and slow down the arm's movements. Press 'v' again to deactivate it.
  - A notice will be displayed on screen when Vernier mode is active.

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Strategies

- Collision/Clearance Limit Avoidance
  - There are a few clearance issues in particular to look out for:
    - Monitor the elbow's position relative to the solar array or forward wall
    - Monitor the end-effector's position relative to the walls and table
- Reducing Task Time
  - Move in more than one direction at once or perform both rotational and translational movements in order to finish the task more quickly.
  - Look for the shortest path between the start position and the target and follow that line as best you can.

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MVL Space Teleoperation Experiment

Strategies

- Moving the Arm to the Target
  - Plan ahead. Before you start working, think about the movements required for the best route and how to avoid obstacles.
    - i.e. Where will the elbow be if you move the end-effector toward the port wall? Will it be too close to a nearby object?
    - When you begin moving the arm, make sure it's doing what you expected. If not, think about what happened and why before moving again.
  - Talk out loud about what you're doing or planning to do while you're working.
    - e.g. "I'm pulling the translational hand controller back; I expect the arm to move toward the forward wall. The elbow is going to get closer to the solar array, but it won't violate the clearance limit."
    - If what you're planning to do doesn't make, you may be able to realize it in advance through hearing yourself say it out loud.

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MVL Space Teleoperation Experiment

Strategies

- Arm Alignment
  - Use the lines on the walls or the edges of fixed objects such as the workbench to determine when the arm is vertical or horizontal
  - Look at all of your views when you are trying to align the arm with the target. In most situations, you CANNOT get all of the information you need from a single view.
- Distance Estimation
  - Remember that the last component of the end-effector is 1m long. You can use it as a guide to ensure that you don't violate the clearance limit and to position the end-effector correctly.
- Maneuvering
  - If you end up with the arm locked up in a hardstop or trapped due to collisions, reset it to its original position by pressing 'r'. Be aware that resets will count against your overall score.

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MVL Space Teleoperation Experiment

Training Schedule

- This is the schedule for how your training will progress.

- Session 1:
  - ☑ Spatial Ability Tests
  - ☑ Orientation
- Session 2:
  - ☐ Training Lesson 1
  - ☐ Training Lesson 2
- Session 3:
  - ☐ Training Lesson 3
  - ☐ Skills Test

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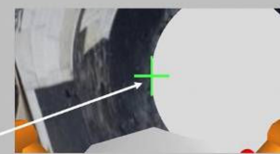
One last thing…

The task described on the following slides gives you one more opportunity to practice with the hand controllers and the robotic arm before your training begins. You will perform this task at the end of each of your three sessions.

Inspection Task

- In addition to moving objects, robotic arms can also be used to inspect objects. You will use the arm to make an inspection video of the tiles on the space shuttle's nose.
  - The inspection will be performed in the internal control mode, and you will perform it five times.
  - Keep the vertical bar of the crosshairs tangent to the circle as you trace its edge in the clockwise direction.



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Inspection Task

- The required hand controller motions will be:
  - Up with the translational controller to move around the circle
  - Right (roll) with the rotational controller to keep the crosshairs aligned
  - Left with the translational controller to stay on the edge of the circle
- Each time the crosshairs reach the red dot on the circle, press SPACEBAR to begin the next inspection.

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Tips for the Inspection

- The most efficient way to perform the inspection is to move both of the controllers at once. Find a balance of how much motion you must make with each controller to steadily and accurately move around the circle.
- Move as quickly as you can around the circle without sacrificing accuracy.
- Be careful that you don't accidentally make multiple motions with the rotational controller at once by unintentionally pushing/pulling or twisting it.
  - It may be helpful to brace the edge of your right hand against the base of the controller.

Please let the experimenter know that you have reached this slide.

Version 2.0 Winter 2008
MVL Space Teleoperation Experiment

APPENDIX E - Experiment 1 Post-Test Questionnaire

Congratulations! You have completed the robotic arm manipulation experiment. Thank you very much for your time and effort. The following questions refer specially to your experience with the desktop virtual reality system. Please answer each question and, if you wish, add any comments.

1. If you experienced any of the following while using the virtual environment, please circle your level of discomfort.

EFFECT	NONE				SEVERE
A. Nausea	1	2	3	4	5
B. Dizziness	1	2	3	4	5
C. Disorientation	1	2	3	4	5
D. Eyestrain	1	2	3	4	5
E. Blurred vision	1	2	3	4	5
F. Sweating	1	2	3	4	5
G. Headache	1	2	3	4	5
H. General discomfort	1	2	3	4	5
I. Mental fatigue	1	2	3	4	5
J. Other __________	1	2	3	4	5

2. How enjoyable/interesting was your interaction with the virtual environment?

Boring 1 2 3 4 5 Captivating

Comments?

3. Rate your proficiency on the following items, after going through the Power Point training:

	LOW				EXPERT
- Understanding the Task	1	2	3	4	5
- Using the hand controllers	1	2	3	4	5
- Understanding camera viewpoints	1	2	3	4	5
- Understanding the frames of reference	1	2	3	4	5

4. How difficult was it for you to translate the arm with the translational controller?

Very difficult 1 2 3 4 5 Very easy

What made it difficult?

5. How difficult was it for you to rotate the end-effecter with the rotational controller?

Very difficult 1 2 3 4 5 Very easy

What made it difficult?

6. To perform a Fly-To task, you mostly monitored:
   - ○ 3 displays at a time
   - ○ 2 displays at a time
   - ○ 1 display at a time

7. To perform a Fly-To task, you mostly translated with:
   - ○ 1 axis at a time
   - ○ 2 axes at a time
   - ○ 3 axes at a time

8. To perform a Fly-To task, you mostly rotated along:
   - ○ 1 axis at a time
   - ○ 2 axes at a time
   - ○ 3 axes at a time

9. To avoid collisions and clearance violations, you: (mark as many as apply)
   - ☐ stayed as far from possible obstacles as possible
   - ☐ foresaw possible collisions and manipulated the arm in advance to increase clearance
   - ☐ moved slowly in risky regions
   - ☐ didn't care about collisions
   - ☐ other: ______________________________

10. To determine your distance from the target, you: (mark as many as apply)
    - ☐ used as many of your camera views as necessary to figure out your position
    - ☐ used the end of the end-effector as a gauge for what 1.5m looks like
    - ☐ took a guess and hoped that you were close enough
    - ☐ other: ______________________________

11. You used the Vernier rate mode to slow down arm movements when: (mark as many as apply)
    - ☐ you wanted more precise control of the arm when aligning with the target
    - ☐ during the entire task; the arm's normal speed was faster than you were comfortable with
    - ☐ you didn't use the Vernier rate mode
    - ☐ other: ______________________________

12. Do you have additional suggestions/comments regarding this experiment?

Thank you! Please return this questionnaire to the experimenter.

APPENDIX F - Experiment 1 Post-Test Questionnaire Results[29]

Subj	Q2	Q3 A	Q3 B	Q3 C	Q3 D	Q4	Q5	Q6	Q7	Q8	Q9	Q10	Q11
201	4	4	4	5	3	4	3	2	3	3	1	0	2
202	4	3	3	5	3	4	4	2	2	1	0	8	2
203	3	3	3	4	2	4	4	2	3	3	1	0	0
204	4	5	4	5	4	5	4	2	3	2	4	0	2
205	5	4	3	5	3	5	4	2	2	2	1	0	0
206	4	4	1	3	1	4	2	2	2	1	4	8	2
207	4	4	4	4	3	4	3	2	2	1	1	4	2
208	4	4	3	3	3	4	2	2	2	2	1	3	0
209	4	3	4	5	5	4	5	2	2	1	5	6	2
210	5	5	4	5	5	4	4	2	2	1	4	0	0
211	4	4	3	5	4	4	3	1	1	1	6	0	0
212	5	5	4	4	4	3	4	2	2	2	8	4	0
213	3	4	4	3	2	5	3	2	3	2	1	8	0
214	4	4	2	4	2	2	3	2	2	2	7	4	2
215	5	4	5	5	4	4	4	2	1	1	4	0	2
216	5	5	4	4	3	4	5	2	2	2	0	4	0
217	5	4	4	4	4	4	3	3	2	1	1	4	0
218	4	5	4	4	4	4	4	3	2	1	5	4	0
219	4	5	4	4	4	4	5	2	2	1	5	6	2
220	3	4	4	4	3	5	5	3	2	1	6	4	0
221	5	4	3	2	3	4	4	2	2	1	4	4	0
222	4	5	3	4	1	3	2	2	2	1	2	5	2

[29] Answer Coding
For questions 2-5, the value in the table corresponds to the answer marked

For questions 6-8, the value corresponds to the number in the marked answer

For questions 9-11, the value in the table corresponds to the answers as follows:
0 = first answer option
1 = second answer option
2 = third answer option
3 = fourth answer option
4 = first and second answer options
5 = second and third answer options
6 = first, second, and third answer options
7 = second, third, and fourth answer options
8 = first and third answer options

APPENDIX G - Experiment 1 Trial Design Summary

Lesson	Trial	Control Mode	Cameras[30]	Target Location
1	1	External	1, EEF, 4	1 (Roll offset)
1	2	External	1, EEF, 4	2 (Pitch offset)
1	3	Internal	2, EEF, 3	1 (Roll offset)
1	4	Internal	1, EEF, 4	3 (Pitch & Roll offset)
2	1	Internal	1, EEF, 4	2 (Pitch offset)
2	2	External	2, EEF, 3	3 (Pitch & Roll offset)
2	3	External	2, EEF, 3	2 (Pitch offset)
2	4	Internal	1, EEF, 4	1 (Roll offset)
3	1	Internal	2, EEF, 3	3 (Pitch & Roll offset)
3	2	External	2, EEF, 3	1 (Roll offset)
3	3	External	1, EEF, 4	3 (Pitch & Roll offset)
3	4	Internal	2, EEF, 3	2 (Pitch offset)
4	1	Internal	2, EEF, 3	1 (Roll offset)
4	2	Internal	1, EEF, 4	2 (Pitch offset)
4	3	External	2, EEF, 3	3 (Pitch & Roll offset)
4	4	External	1, EEF, 4	1 (Roll offset)
4	5	External	2, EEF, 3	2 (Pitch offset)
4	6	Internal	1, EEF, 4	3 (Pitch & Roll offset)

[30] Cameras 1 and 4 were the "low disparity" cameras; cameras 2 and 3 were the "high disparity" cameras.

APPENDIX H - Experiment 2 Subject Basic Data[31,32]

Subj	Gender	Writing Hand	MRT	PTA	PSVT	BMC
301	M	Right	22	17.60	9	25.99
302	M	Right	22	26.47	19	13.68
303	M	Right	28	26.43	27	30.51
304	M	Left	22	26.17	16	20.65
401	M	Right	30	23.35	24	22.95
403	M	Right	10	21.53	7	31.50
408	F	Left	16	20.60	12	31.96
410	M	Right	20	21.78	23	33.33
415	M	Right	20	18.92	15	32.30
417	M	Right	24	26.48	19	32.07
421	M	Right	12	19.07	20	32.38
430	M	Right	29	19.67	11	26.95
433	M	Right	35	24.57	23	30.94
434	M	Left	22	19.37	18	31.73
436	F	Right	8	19.73	14	30.08
437	F	Right	4	13.18	7	3.19
439	F	Right	5	10.38	5	-1.68
440	M	Right	36	24.52	21	24.88
441	M	Right	11	18.01	12	30.42
442	F	Right	10	16.53	8	26.52

Secondary Operator Subject Group Demographics

Group	N	Males	Females	L/R Handed
A	5	4	1	1 / 4
B	5	4	1	1 / 4
C	4	4	0	0 / 5
D	5	3	2	1 / 4

[31] 300 range = pilot subjects. 401-429 = repeating subjects; number corresponds to Experiment 1 subject number. 301 and 303 were also repeating subjects. 430+ = new subjects.

[32] Subjects highlighted in gray were excluded from the secondary operator analysis

APPENDIX I - Experiment 2 Pre-Test Questionnaire

Gender: F M **Age**: _____

Writing Hand: Right Left **Course #**: ______

Colorblind? Y N (If yes, explain: ____)

10. **Do you have any experience with Virtual 3-D environments (e.g. 3-D games, CAD, 3-D graphic design, etc.)?**

(Yes No) (If "Yes," can you please describe this experience?)

11. **Do you have any experience with joysticks or game controllers? (e.g. computer games, video games, robotic manipulation)**

(Yes No) (If "Yes," can you please describe this experience?)

12. **How many hours per day do you use the computer?**
    ☐ 0 ☐ 1 – 3 ☐ 3 – 5 ☐ 5 – 7 ☐ More than 7

13. **What do you typically use the computer for? (Please check all that apply)**
    ☐ Email/word processing/web browsing ☐ Design (Graphical/Mechanical)
    ☐ Programming ☐ Gaming
    ☐ Other____

14. **Have you ever or do you now have a habit of playing video/computer games?**

(Yes No) (If "No," go to question 10)

15. **What was your age when you started playing video/computer games?**
    ☐ < 5 ☐ 5 – 12 ☐ 12 – 18 ☐ 18- 25 ☐ > 25

16. **On average, how often (hours/week) did you play video/ computer games <u>when you played the most frequently</u>?**
    ☐ 1 – 3 ☐ 3 – 7 ☐ 7 –14 ☐ 14 – 28 ☐ > 28

    How many years ago was that?
    ☐ 0 ☐ 3 – 5 ☐ 5 – 10 ☐ 10 – 15 ☐ > 15

17. **On average, how often (hours/week) have you played video/computer games <u>in the past 3 years</u>?**
☐ 0 ☐ 1 – 3 ☐ 3 – 7 ☐ 7 –14 ☐ 14 – 28 ☐ > 28

18. **What kind of video/computer games do you play the most? (check as many as apply)**
☐ First person
☐ Role-playing/Strategy
☐ Arcade/Fighting (please specify: 2D 3D)
☐ Simulation (driving, flying)
☐ Sports (which? ______________________________)
☐ Other ______________

11. **Have you ever taken any spatial ability tests before?**
☐ Yes, for a previous robotics experiment with the MVL
☐ Yes, for some other reason (please list: ____
____)
☐ No

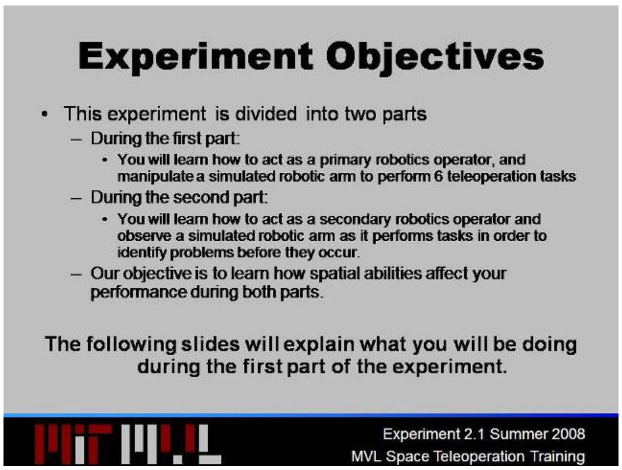
12. **Personal Measurements**
Height:____________
Leg Length: ____________
Arm Length:____________

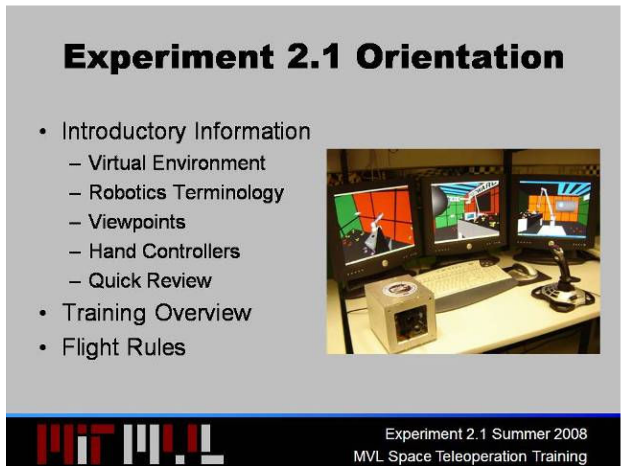
Thank you. Please give this questionnaire back to the experimenter.

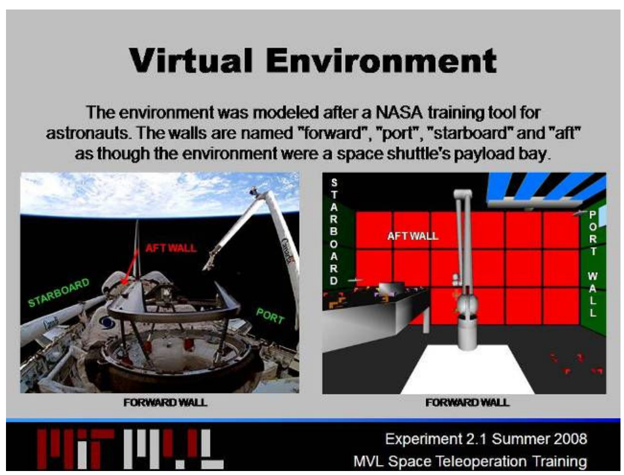
APPENDIX J - Experiment 2 Pre-Test Questionnaire Results

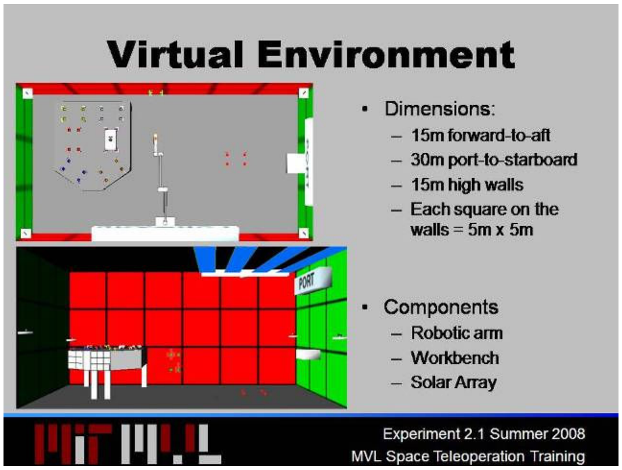
	3-D Exp?	3-D Type	Contr Exp?	Contr Type	Comp Hours	Comp Usage	Game Habit?	Game Age	Game Hours	Game Years	Game Recent	Game Type	Prev SA
301	Y	CAD	Y	Comp	3-5	E & P	Y	5-12	1-3	10-15	0	Sim	Yes, MVL
302	Y	G & CAD	Y	Video	3-5	E-mail	Y	5-12	7-14	5-10	1-3	RP,Sp	No
303	Y	G & CAD	Y	Video	7+	E & P	Y	5-12	14-28	3-5	3	FP,FP,Si	Yes, MVL
304	Y	G & CAD	Y	Video	5-7	E & G	Y	< 5	28+	5-10	7-14	FP,RP	No
401	Y	Design	Y	Comp	7+	E & D	Y	5-12	3-7	10-15	0	FP,RP,Si	Yes, Other
415	Y	G & CAD	Y	C&V	3-5	E,P,G	Y	5-12	7-14	10-15	3-7	RP,Other	Yes, MVL
408	Y	CAD	Y	Robotics	5-7	E & D	Y	5-12	3-7	5-10	0	Arcade	Yes, MVL
410	Y	CAD	Y	Video	5-7	E-mail	Y	5-12	3-7	15+	0	RP	Yes, MVL
430	Y	CAD	Y	Video	7+	E,D,P	N	N/A	N/A	N/A	N/A	N/A	No
440	Y	CAD & D	Y	V&R	7+	E-mail	Y	5-12	14-28	3-5	1-3	RP,Si,Sp	No
439	Y	G&D	N	N/A	7+	E & P	Y	5-12	7-14	3-5	1-3	RP	No
437	N	N/A	Y	Video	3-5	E-mail	N	N/A	N/A	N/A	N/A	N/A	No
433	Y	Games	N	N/A	5-7	E & G	Y	5-12	14-28	3-5	3-7	RP	No
441	Y	G & CAD	N	N/A	7+	E,D,P	Y	5-12	14-28	3-5	1-3	FP,RP	No
421	Y	Games	Y	Comp	7+	E-mail	Y	12-18	3-7	10-15	0	FP,Sp,Oth	Yes, MVL
417	Y	CAD	Y	V& Flight Sim	5-7	E-mail	Y	5-12	3-7	10-15	1-3	Sim	Yes, MVL
442	Y	CAD	Y	Video	5-7	E-mail	N	N/A	N/A	N/A	N/A	N/A	No
436	Y	G & CAD	Y	Video	5-7	E & D	Y	5-12	1-3	10-15	0	Arcade	No
419	Y	G & CAD	Y	C&V	5-7	E,P,G	Y	< 5	28+	3-5	1-3	FP,RP,A	Yes, MVL
403	Y	G&C&D	Y	C&V	5-7	E,D,P,G	Y	5-12	7-14	5-10	0	FP	Yes, MVL
434	Y	G & CAD	Y	V& Flight Sim	7+	E & P	Y	5-12	14-28	10-15	1-3	FP,RP,Si,Sp	Yes, MVL

APPENDIX K - Experiment 2 Training – Primary








Virtual Environment
Dimensions:
15m forward-to-aft
30m port-to-starboard
15m high walls
Each square on the walls = 5m x 5m
Components
Robotic arm
Workbench
Solar Array
PORT
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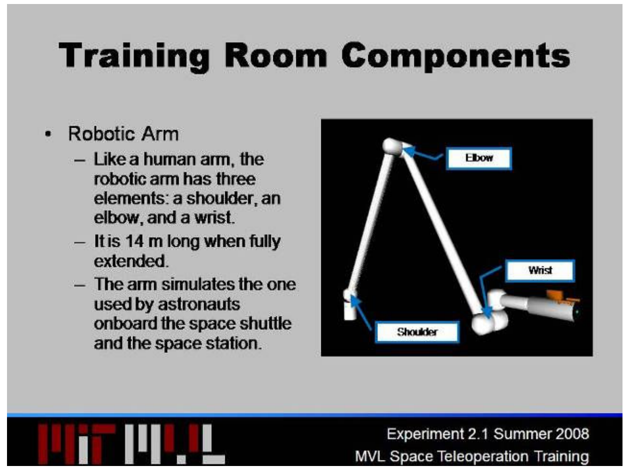
Training Room Components
Robotic Arm
Like a human arm, the robotic arm has three elements: a shoulder, an elbow, and a wrist.
It is 14 m long when fully extended.
The arm simulates the one used by astronauts onboard the space shuttle and the space station.
Elbow
Wrist
Shoulder
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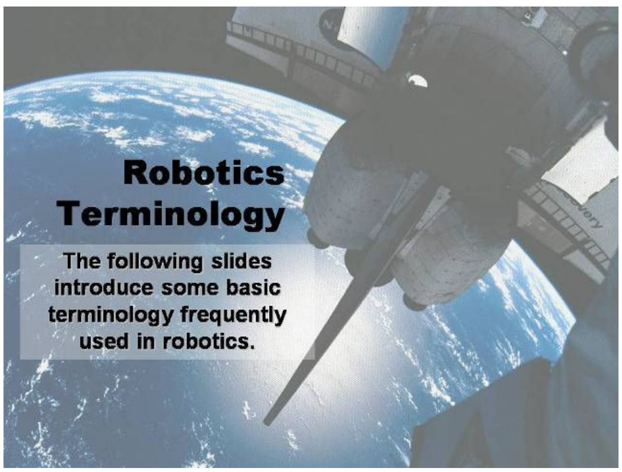
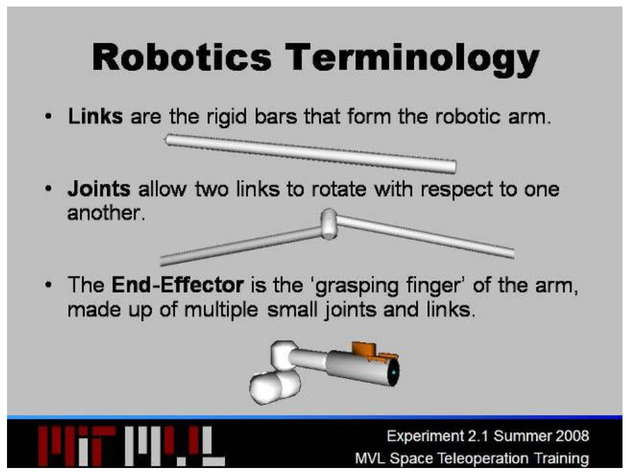

Robotics Terminology
The following slides introduce some basic terminology frequently used in robotics.


Robotics Terminology
Links are the rigid bars that form the robotic arm.
Joints allow two links to rotate with respect to one another.
The End-Effector is the 'grasping finger' of the arm, made up of multiple small joints and links.
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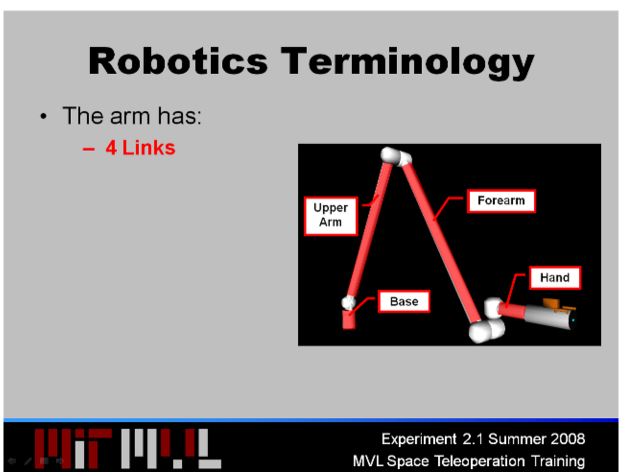
Robotics Terminology
The arm has:
4 Links
Upper Arm
Forearm
Hand
Base
Experiment 2.1 Summer 2008
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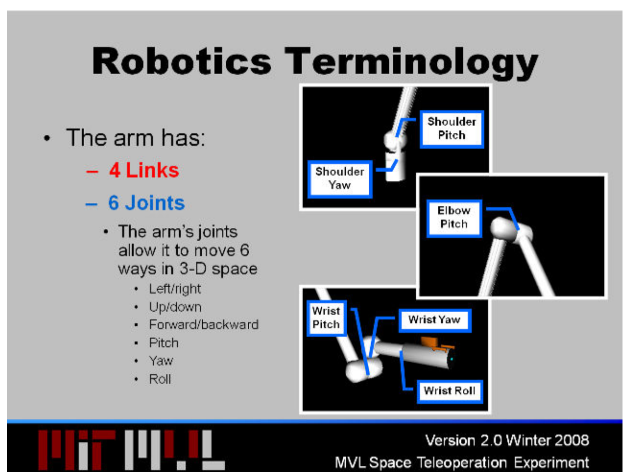
Robotics Terminology
The arm has:
4 Links
6 Joints
The arm's joints allow it to move 6 ways in 3-D space
Left/right
Up/down
Forward/backward
Pitch
Yaw
Roll
Shoulder Pitch
Shoulder Yaw
Elbow Pitch
Wrist Pitch
Wrist Yaw
Wrist Roll
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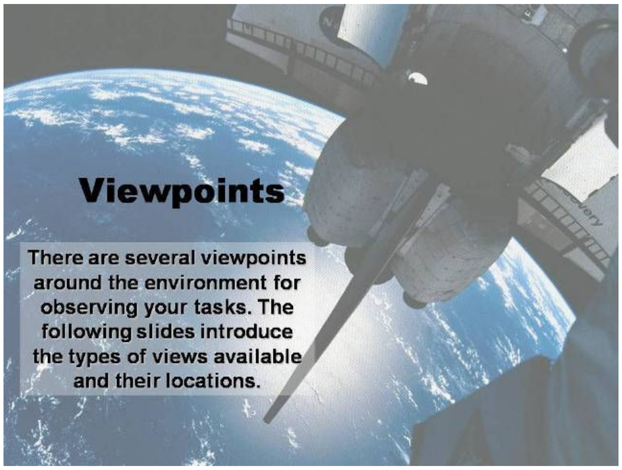


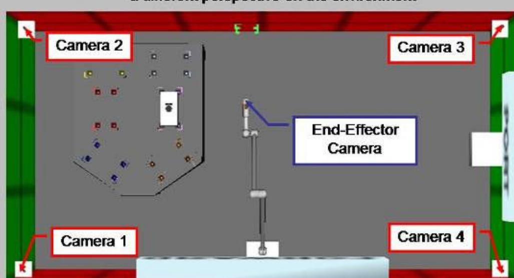
Viewpoints

- You will have three monitors giving you views of the environment.
- There are 5 possible views:
  - Four views from numbered cameras inside the room (one is located in each corner)
  - One view from a camera placed on the end of the arm (the End-Effector Camera)
- The views will be selected for you.

Experiment 2.1 Summer 2008
MVL Space Teleoperation Training

Viewpoints

Each of the 5 views (4 numbered cameras and the End-Effector Camera) gives a different perspective on the environment



Experiment 2.1 Summer 2008
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Viewpoints

The following slides show each of the viewpoints.

The viewpoints will be shown on the right. On the left, you can see where the camera is located.

Experiment 2.1 Summer 2008
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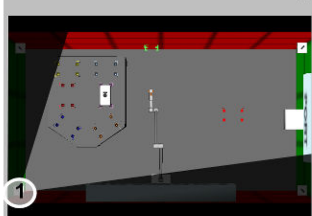
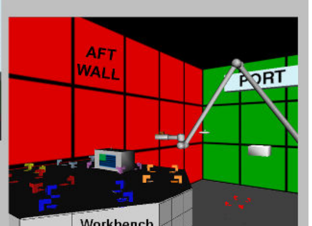
Viewpoints





Experiment 2.1 Summer 2008
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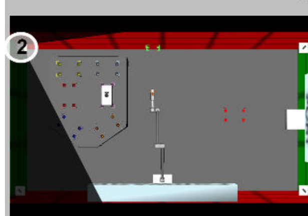
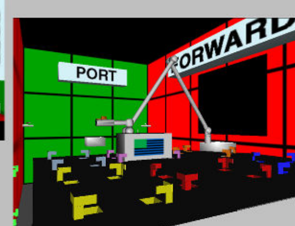
Viewpoints





Experiment 2.1 Summer 2008
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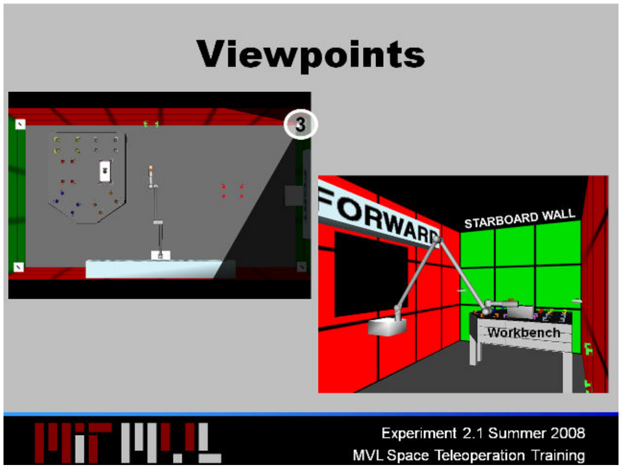
Viewpoints
3
STARBOARD WALL
Workbench
Experiment 2.1 Summer 2008
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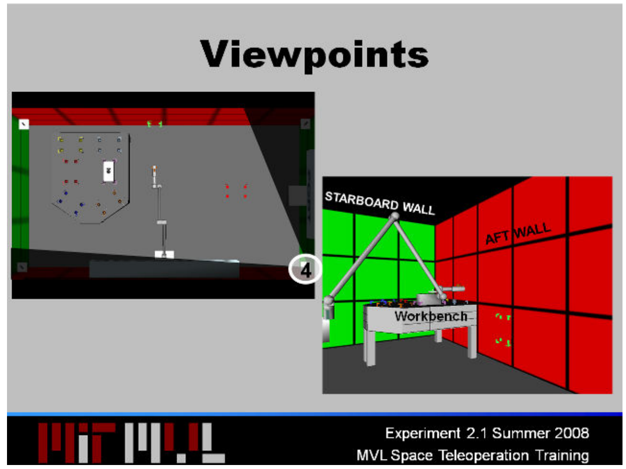
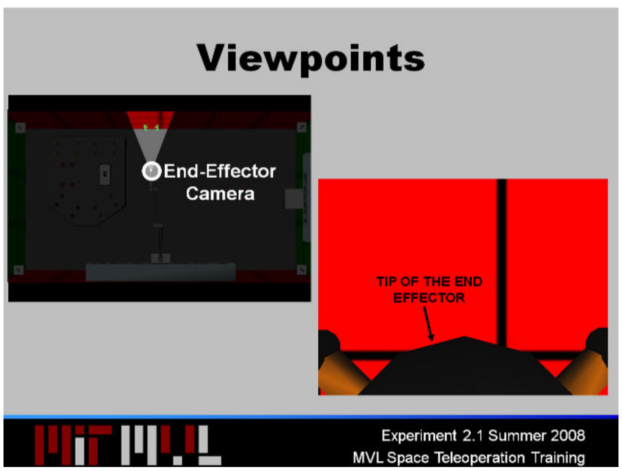
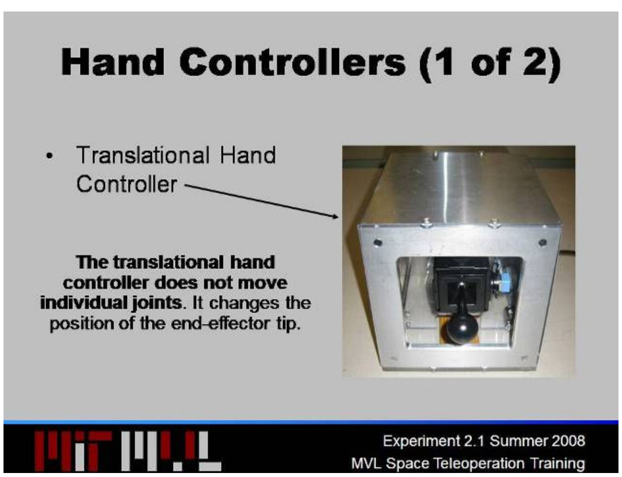
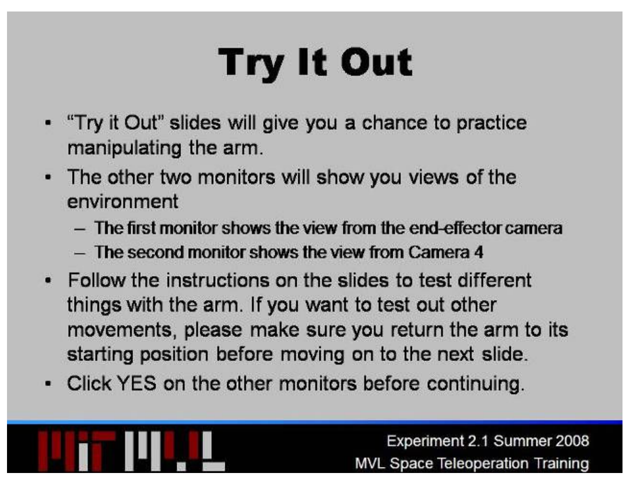
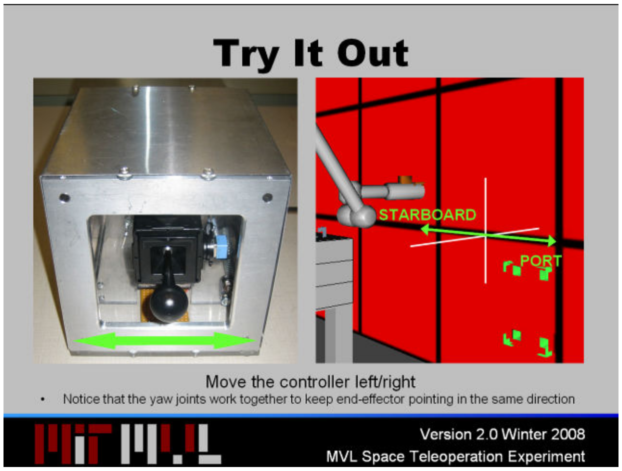

Viewpoints
4
STARBOARD WALL
AFT WALL
Workbench
Experiment 2.1 Summer 2008
MVL Space Teleoperation Training

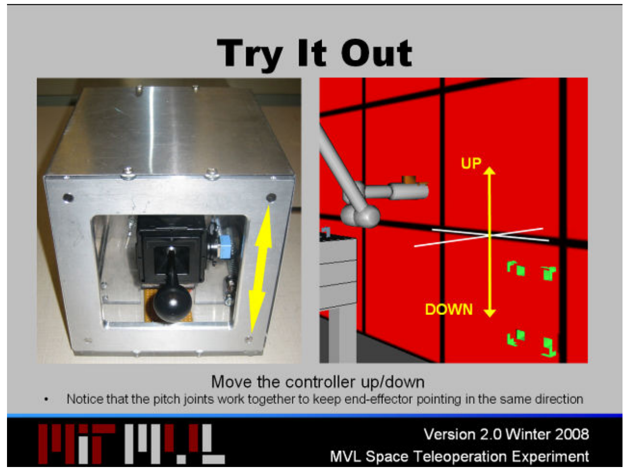

Viewpoints
End-Effector Camera
TIP OF THE END EFFECTOR
Experiment 2.1 Summer 2008
MVL Space Teleoperation Training

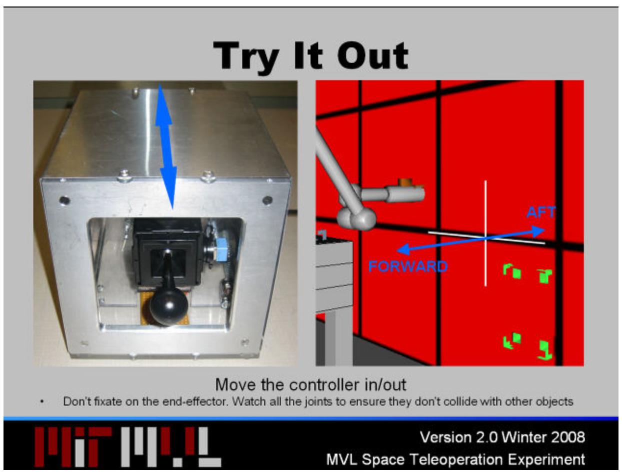

Hand Controllers
There are two hand controllers. The one on your left translates (moves forward/backward, left/right, or up/down) and the one on your right rotates the arm.

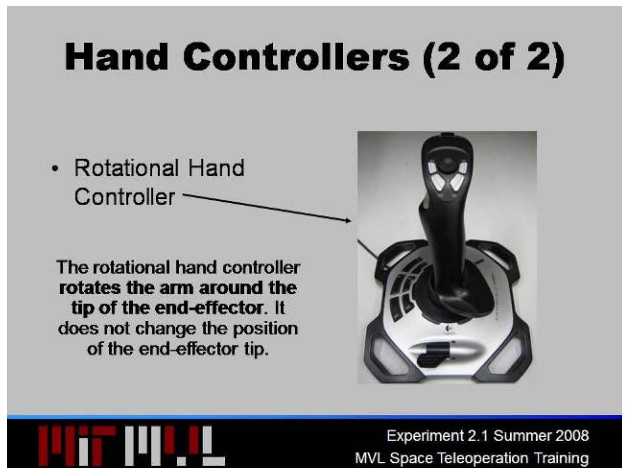

Hand Controllers (1 of 2)
• Translational Hand Controller
The translational hand controller does not move individual joints. It changes the position of the end-effector tip.
Experiment 2.1 Summer 2008
MVL Space Teleoperation Training

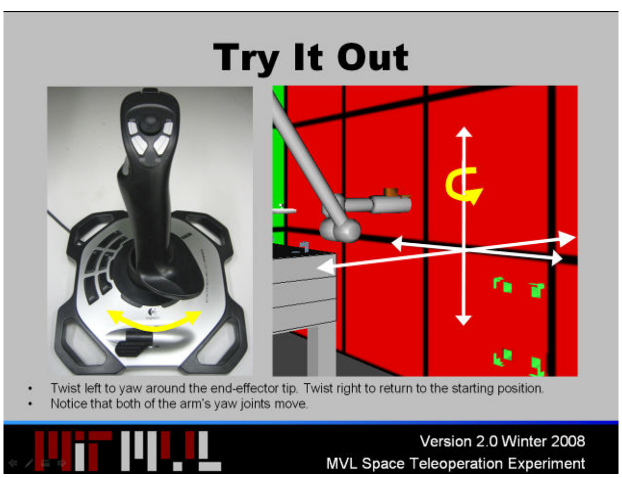

Try It Out
• "Try it Out" slides will give you a chance to practice manipulating the arm.
• The other two monitors will show you views of the environment
– The first monitor shows the view from the end-effector camera
– The second monitor shows the view from Camera 4
• Follow the instructions on the slides to test different things with the arm. If you want to test out other movements, please make sure you return the arm to its starting position before moving on to the next slide.
• Click YES on the other monitors before continuing.
Experiment 2.1 Summer 2008
MVL Space Teleoperation Training

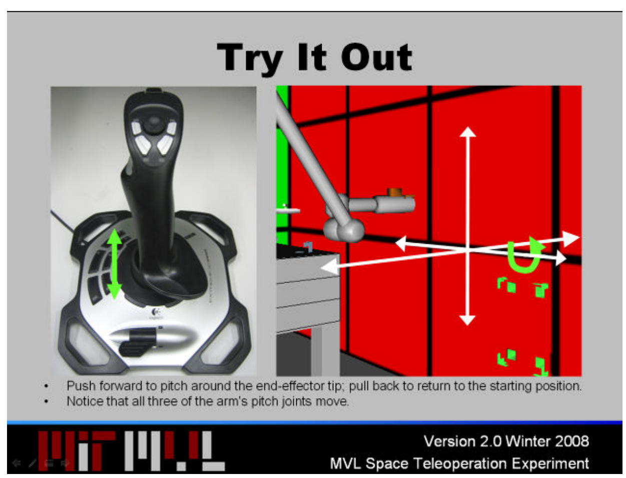

Try It Out
STARBOARD
PORT
Move the controller left/right
• Notice that the yaw joints work together to keep end-effector pointing in the same direction
Version 2.0 Winter 2008
MVL Space Teleoperation Experiment


Try It Out
UP
DOWN
Move the controller up/down
• Notice that the pitch joints work together to keep end-effector pointing in the same direction
Version 2.0 Winter 2008
MVL Space Teleoperation Experiment

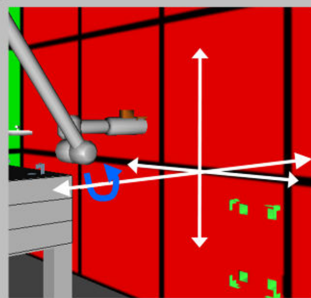

Try It Out
AFT
FORWARD
Move the controller in/out
• Don't fixate on the end-effector. Watch all the joints to ensure they don't collide with other objects
Version 2.0 Winter 2008
MVL Space Teleoperation Experiment


Hand Controllers (2 of 2)
• Rotational Hand Controller
The rotational hand controller rotates the arm around the tip of the end-effector. It does not change the position of the end-effector tip.
Experiment 2.1 Summer 2008
MVL Space Teleoperation Training


Try It Out
• Twist left to yaw around the end-effector tip. Twist right to return to the starting position.
• Notice that both of the arm's yaw joints move.
Version 2.0 Winter 2008
MVL Space Teleoperation Experiment

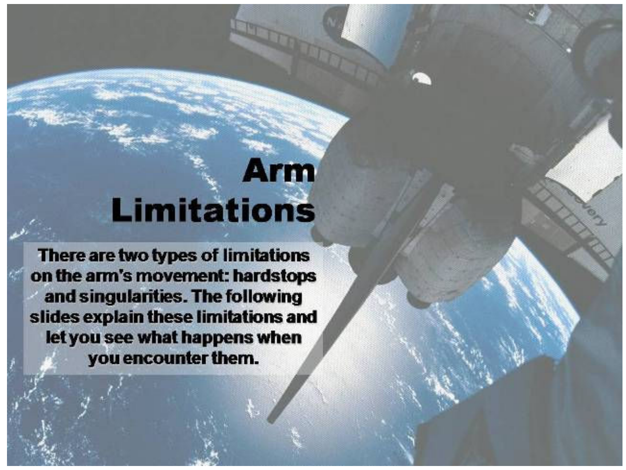

Try It Out
• Push forward to pitch around the end-effector tip; pull back to return to the starting position.
• Notice that all three of the arm's pitch joints move.
Version 2.0 Winter 2008
MVL Space Teleoperation Experiment

Try It Out



- Push right to roll around the end-effector tip; push left to return to the starting position.
- Notice that the end-effector roll joint is the only one that moves.

Version 2.0 Winter 2008
MVL Space Teleoperation Experiment



Arm Limitations

There are two types of limitations on the arm's movement: hardstops and singularities. The following slides explain these limitations and let you see what happens when you encounter them.

Hardstops

- Hardstops are the physical limits on how far a joint can rotate.
- The Joint Angle Info Display will show what each joint is doing.
  - Each slider bar shows where the joint's current angle falls within its possible range of motion.
  - Look at this display frequently while you are moving the arm.
- Press 'i' to turn on the display. You can change its position or hide it by pressing 'i' again.

Experiment 2.1 Summer 2008
MVL Space Teleoperation Training

Hardstops

- The Joint Angle Info Display will warn you about hardstops.
  - If the Info Display turns yellow, you are within 10° of a hardstop.
    - Look for this warning in order to avoid actually reaching the hardstop.
  - If the Info Display turns red, you have reached a hardstop.
    - This notice is also displayed on the screen: HARDSTOP
    - Move the arm in the reverse direction in order to free the joint

Experiment 2.1 Summer 2008
MVL Space Teleoperation Training

Try It Out – Hardstops

- Follow these steps to see what happens when you reach the wrist roll hardstop:
  - Push the Rotational Hand Controller right and hold it there
    - Watch the angle and the slider bar change as the joint moves
    - Notice the yellow warning as you get close to the hardstop, and the red warning when you reach it.
  - Push the controller back to the left to return to the starting position (Wr Roll centered)

Experiment 2.1 Summer 2008
MVL Space Teleoperation Training

Singularities

If the arm is put in one of the following positions, known as singularities, it is unable to continue moving.

When the Elbow Pitch joint is at 0°, all of the arm's joints lock up and the word "SINGULARITY" is displayed on the screen. Move in the opposite direction to free the arm.

When the Wrist Yaw joint is near ±90°, the arm's joints will be brought close to a hardstop to avoid the singularity. Be very careful to avoid this position.

When the Wrist Roll joint is near ±90°, the Wrist Pitch joint locks up. Move the Wrist Roll joint away from ±90° to regain normal function.

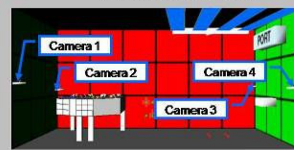
Experiment 2.1 Summer 2008
MVL Space Teleoperation Training

Try It Out – Singularities

- Follow these steps to see what happens when you reach the elbow pitch singularity:
  - Push the translational hand controller to the right and hold it there.
    - Watch the arm move until it hits the singularity. Notice the warning that is displayed on the screen.
  - Move the hand controller back to the left in order to recover.

Review of Important Concepts

- Camera Viewpoints
  - The BORIS environment has **5 viewpoints**
    - 4 numbered views in the room
    - 1 mobile view on the arm



- Hand Controllers
  - Two kinds:
    - **Translational** (on your left)
    - **Rotational** (on your right)
- Arm Limitations
  - **Hardstops** are the physical limits on how far a joint can rotate.
  - When the arm reaches a **singularity**, it cannot determine how to continue moving.

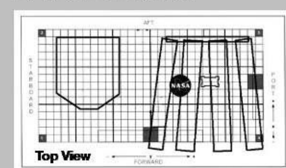
Experiment 2.1 Summer 2008
MVL Space Teleoperation Training

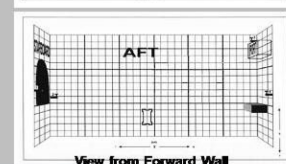
Training Overview

Now that you know how the arm and environment work, the following slides will tell you more about what you'll be doing in the first part of the experiment.

Training Overview

- During robotics training, astronauts learn to maneuver the arm to a fixed point. They use views from multiple cameras to determine their accuracy.
- You will be provided two maps of the environment, shown on the right, and will be asked to bring the arm to a specific target point in the environment.





Experiment 2.1 Summer 2008
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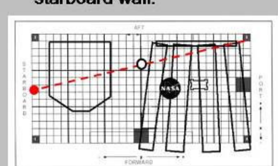
Training Overview

- Your target position is shown as an open circle on the map. The dotted lines show the view of this position from each camera.
- Move the arm so that the tip of the end-effector is at the target position. When the arm is properly positioned, the tip of the end-effector will appear to cover the point at the end of each of the dotted lines.
- The example below shows that, when looking from camera 3, the end-effector should look like it is in line with the center of the starboard wall.



Experiment 2.1 Summer 2008
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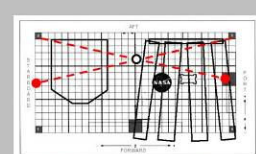
Training Overview

You will need all 3 views to align properly. This example shows how two views show alignment along two axes, but a third view (and the second map) will be needed to determine the correct position along the up/down axis.



Camera 2


Camera 3

Experiment 2.1 Summer 2008
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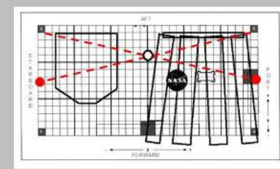
Training Overview

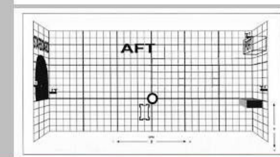
- At the beginning of each activity, a prompt will tell you:
  - Which target point you will be aiming for, so that you can locate the correct map
  - Which cameras you will be using so that you can find the right lines on the map
- Before telling the program to continue, look at the map and figure out what you need to look for in the cameras and where you need to move the arm.
- Use the lines on the walls as references points. The lines that are visible in the environment are the darker lines on the maps.

Training Practice

Practice with the example shown on the right to practice. You will have a paper map to refer to.

Please let the experimenter know you have reached this slide.





Training Performance

- Work as quickly as you can without making errors.
- There is no time limit, but you will be given a rating based on errors and speed.

Performance Ratings

1. Corps Applicant (worst)
2. Astronaut Candidate
3. Mission Specialist
4. Flight Engineer
5. Lead Arm Operator (best)

- Your target position also includes a desired orientation (pitch or roll angle) - don't forget this step!
  - Pitching up means to have the tip of the end-effector pointed upwards; pitching down is the opposite.
- When you are finished positioning the arm, press SPACEBAR to see how accurate you were and to go on to the next task.
- You will complete six tasks in total before receiving your performance rating.

Flight Rules

- To help avoid collisions, there is a clearance limit of 0.6m between the arm and all obstacles/walls
  - A warning will be shown on the screen when any part of the arm comes within this limit.

Clearance Violation

  - Look for what has caused the clearance violation and move away to remove the warning.
  - As shown above, the fact that the very last section of the end-effector is 1m long can be used as an estimating guide.
- If a collision occurs, the arm will bounce off of the object, and this warning will be displayed on the screen:

COLLISION

Flight Rules

- Start each activity by moving to the general location where the target is, then perform more precise positioning of the end-effector.
- Think about the movements required for the shortest route to the target while avoiding clearance violations.
- When you begin moving the arm, make sure that it's doing what you expected. If not, stop moving and think about what happened and why.
- Talk aloud about what you're doing or planning to do while working.
  - e.g. "I'm pulling the translational hand controller back; the arm will move toward the forward wall. The elbow is going to get closer to the wall, but won't violate the clearance limit."
  - This will help develop skills for the second part of the experiment. Also, you may be able to catch mistakes by hearing yourself say it out loud.

Strategies

- Collision/Clearance Limit Avoidance
  - There are a few specific clearance issues to look out for:
    - Monitor the elbow's position relative to the solar array or forward wall
    - Monitor the end-effector's position relative to the walls and table
- Reducing Task Time
  - Move in more than one direction at once to finish the task more quickly.
  - Look for the shortest path between the start position and the target and follow that line as best you can.

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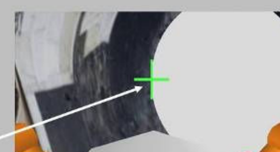
Strategies

- Arm Positioning
  - Use the lines on the walls or the edges of fixed objects such as the workbench to determine orientation angles
  - Remember to look at ALL of the viewpoints
- Maneuvering
  - If you end up with the arm locked up in a hardstop or trapped due to collisions, you can reset it to its original position by pressing 'r'. But don't use this too often; resets will lower your rating.

Experiment 2.1 Summer 2008
MVL Space Teleoperation Training

Inspection Task

- Robotic arms can also be used to inspect objects. You will use the arm to make an inspection video of the tiles on the space shuttle's nose.
  - You will do the inspection four times in a row.
  - Keep the vertical bar of the crosshairs tangent to the circle as you trace its edge in the clockwise direction.



Experiment 2.1 Summer 2008
MVL Space Teleoperation Training

Inspection Task

- The required hand controller motions will be:
  - Up with the translational controller to move around the circle
  - Right (roll) with the rotational controller to keep the crosshairs aligned
  - Left with the translational controller to stay on the edge of the circle
- Each time the crosshairs reach the red dot on the circle, press SPACEBAR to begin the next inspection.

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Tips for the Inspection

- The most efficient way to perform the inspection is to move both of the controllers at once. Find a balance of how much motion you must make with each controller to steadily and accurately move around the circle.
- Move as quickly as you can around the circle without sacrificing accuracy.
- Be careful that you don't accidentally make multiple motions with the rotational controller at once by unintentionally pushing/pulling or twisting it.
  - It may be helpful to brace the edge of your right hand against the base of the controller.

Please let the experimenter know that you have reached this slide.

Experiment 2.1 Summer 2008
MVL Space Teleoperation Training

APPENDIX L - Experiment 2 Post-Test Questionnaire 1

You're halfway done with the experiment! Before you forget details about your experiences, we'd like to get some information about your training. Please answer each question and, if you wish, add any comments.

1. If you experienced any of the following, please circle your level of discomfort:

EFFECT	NONE				SEVERE
A. Nausea	1	2	3	4	5
B. Dizziness	1	2	3	4	5
C. Disorientation	1	2	3	4	5
D. Eyestrain	1	2	3	4	5
E. Blurred vision	1	2	3	4	5
F. Sweating	1	2	3	4	5
G. Headache	1	2	3	4	5
H. General discomfort	1	2	3	4	5
I. Mental fatigue	1	2	3	4	5
J. Other __________	1	2	3	4	5

2. How enjoyable/interesting was your interaction with the virtual environment?

Boring 1 2 3 4 5 Captivating

Comments?

3. Rate your proficiency on the following items, after going through the Power Point training:

	LOW				EXPERT
- Understanding the Task	1	2	3	4	5
- Using the hand controllers	1	2	3	4	5
- Understanding the camera viewpoints	1	2	3	4	5

4. How difficult was it for you to translate the arm with the translational controller?

Very difficult 1 2 3 4 5 Very easy

What made it difficult?

5. How difficult was it for you to rotate the end-effecter with the rotational controller?

Very difficult 1 2 3 4 5 Very easy

What made it difficult?

6. To perform the task, you:
   - ○ Spent about equal amounts of time looking at each of the three displays
   - ○ Spent most of your time looking at the two displays with external cameras
   - ○ Spent most of your time looking at the one display with the camera on the arm
   - ○ Spent most of your time looking at one external camera and the camera on the arm
   - ○ Other: ____

7. To precisely align the arm at the end of the task, you mostly:
   - ○ Performed the translational alignment, then rotational
   - ○ Performed the rotational alignment, then translational
   - ○ Performed translational and rotational alignment at the same time

8. When maneuvering the arm to pitch up or pitch down, you mostly:
   - ○ Used the lines on the wall to estimate the angle
   - ○ Used other objects in the room (table edge, etc) to estimate the angle
   - ○ Used the Joint Angle Info Display to estimate the angle
   - ○ Other: ____

9. To avoid collisions and clearance violations, you: (mark as many as apply)
   - ☐ stayed as far from possible obstacles as possible
   - ☐ foresaw possible collisions and manipulated the arm in advance to increase clearance
   - ☐ didn't care about clearance violations or collisions
   - ☐ other: ______________________________

10. When using cameras 2 and 3, did you flip the map upside down to help with determining alignment?
    - ○ Yes, in the beginning
    - ○ Yes, throughout the experiment
    - ○ No

11. Did you try to memorize the layout of the environment during your orientation, or wait and learn it as you went through the tasks?
    - ○ I spent a lot of time studying the pictures of the environment to figure things out
    - ○ I decided to just figure out where things were as I was working with the arm
    - ○ Other: ____

12. Do you have additional suggestions/comments regarding this part of the experiment?

Thank you! Please return this questionnaire to the experimenter.

APPENDIX M - Experiment 2 Post-Test Questionnaire 1 Results[33]

Subj	Q2	Q3 A	Q3 B	Q3 C	Q4	Q5	Q6	Q7	Q8	Q9	Q10	Q11
302	4	5	4	4	4	5	1	0	0	1	2	0
303	5	4	4	5	5	5	1	0	0	0	2	0
304	4	4	4	3	5	3	2	0	0	1	2	0
401	4	3	4	3	5	4	0	0	0	1	2	0
415	4	5	3	3	5	3	1	0	0	0	2	1
408	2	4	3	2	4	4	1	0	0	2	2	1
410	5	5	5	4	5	5	1	0	0	0	2	2
432	3	4	4	4	5	2	0	0	0	2	2	1
440	5	5	5	5	5	5	1	0	0	1	2	1
439	4	4	3	4	5	3	3	0	0	2	1	1
437	5	4	4	4	5	5	1	0	0	1	2	1
433	4	5	5	5	5	5	1	0	0	1	2	1
441	5	4	4	2	4	3	3	0	0	1	2	1
421	4	4	4	3	5	5	1	0	0	1	0	1
417	4	4	4	4	4	4	0	0	0	1	2	5
442	3	3	4	2	4	4	1	0	0	1	2	1
436	4	4	3	3	3	2	1	0	0	4	2	0
403	2	3	3	3	4	5	3	0	0	1	2	1
434	5	4	4	4	5	4	0	0	0	1	2	0

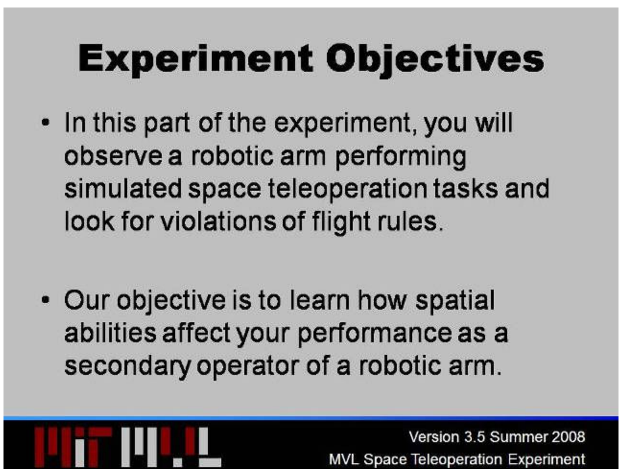
[33] Answer Coding

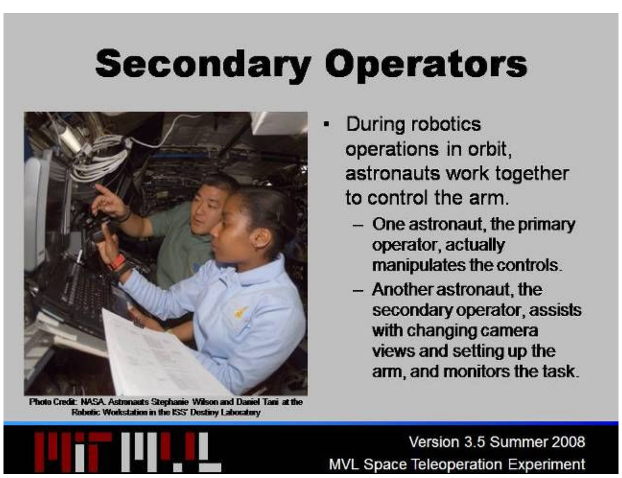
For questions 2-5, the value in the table corresponds to the answer marked

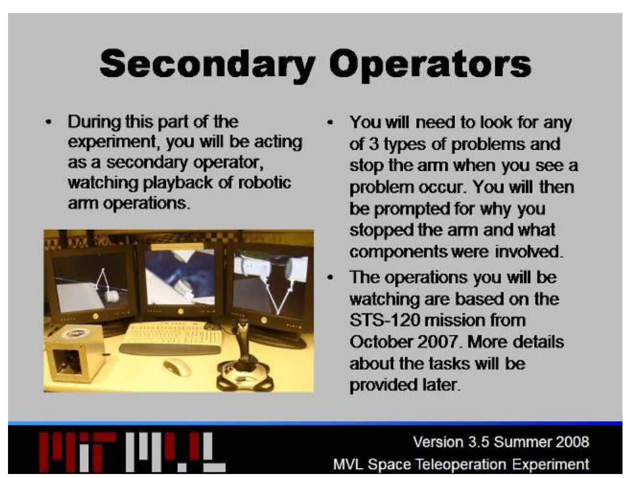
For questions 6-11, the value in the table corresponds to the answers as follows:

0 = first answer option
1 = second answer option
2 = third answer option
3 = fourth answer option
4 = first, second, and fourth answer options
5 = first and second answer options

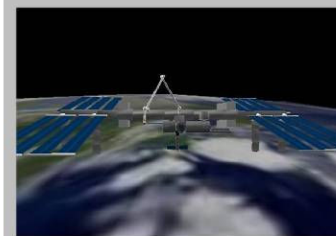
APPENDIX N - Experiment 2 Training – Secondary







Virtual Environment



- International Space Station (ISS)
  - Components
    - Core Modules
    - Truss & Solar Arrays
    - Robotic Arm & Payload
    - Shuttle (some tasks)

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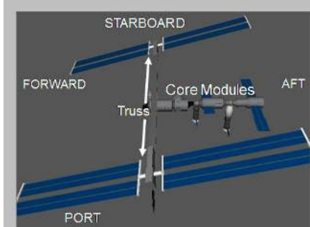
International Space Station



- Core Modules
  - The Core Modules make up the habitable space of the station.
  - They are located on the forward/aft axis of the ISS
- Truss and Solar Arrays
  - The truss is mounted at the forward end of the Core Modules.
  - It is located on the port/starboard axis of the ISS

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International Space Station

- Now you can spend a few minutes navigating through the environment.
  - Use the keyboard controls to move the camera (right monitor).
  - The blue dot on the left monitor shows where the camera is located.
- Things to try:
  - Get familiar with what the truss looks like and where the modules are located.
  - Estimate how far along the truss the arm can reach.

Press the following keys on the keyboard to move to:

p = port	s = starboard
u = upwards	d =downwards
a = aft	f = forward

Use the arrow keys to yaw to the left or right.

Click YES on the dialogue box on the other monitors to begin.
When you are finished, press ESCAPE on the keyboard.

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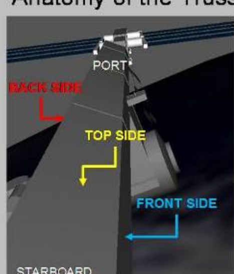
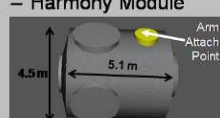
International Space Station

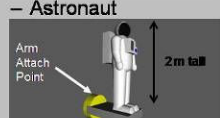
- Anatomy of the Truss



- Payloads
  - Harmony Module



  - Astronaut



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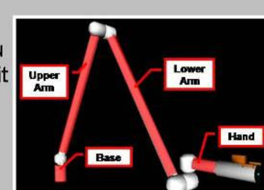
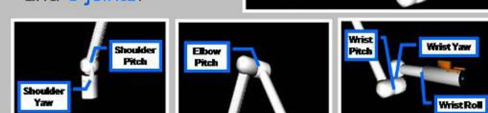
Robotic Arm

- This robotic arm is similar to the one you used previously, but it is longer (17m long)
- Like that arm, this one also has 4 links and 6 joints.





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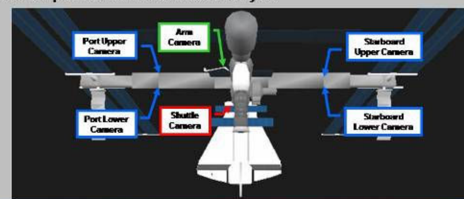
Viewpoints

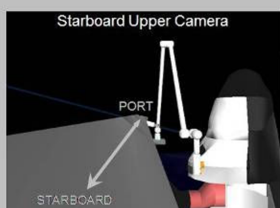
There are many viewpoints in this environment for observing your tasks. The following slides introduce the types of views available and their locations.

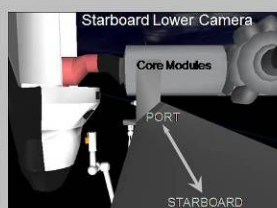
Viewpoints

- The three monitors give different views of the environment and can show any of 6 viewpoints:
  - Four from cameras on the Truss
  - One from a camera in the Shuttle's payload bay
  - One from a camera placed at the arm's elbow
- The viewpoints will be selected for you



Viewpoints





- Both of the cameras on the lower side of the truss are mounted upside down.
- The pictures above show the views from the starboard upper and starboard lower cameras.

Lesson Overviews

For this part of the experiment, you will be a secondary operator practicing for 4 types of tasks (lessons) during the STS-120 Shuttle mission. The following slides will explain these lessons.

Lesson Overviews

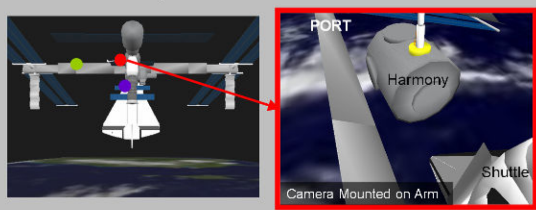
- You will perform 8 activities for each of 4 lessons
- For each lesson:
  - The camera views and the arm's start- and end-points will stay constant
  - The path that the arm takes from its start-point to the end-point will vary.
- The environment in each lesson is slightly different:
  - The payload on the arm will be the Harmony Module for Lessons 1, 3, & 4 and an Astronaut for Lesson 2
  - You will be able to see the Shuttle for Lessons 1 and 2

Lesson One

- When the Shuttle first arrived at the ISS during STS-120, the crew needed to move the new Harmony module from the Shuttle to the port side of the Unity module.
- As the secondary operator, you will have the three camera views shown successively below:

Lesson One

- When the Shuttle first arrived at the ISS during STS-120, the crew needed to move the new Harmony module from the Shuttle to the port side of the Unity module.
- As the secondary operator, you will have the three camera views shown successively below:



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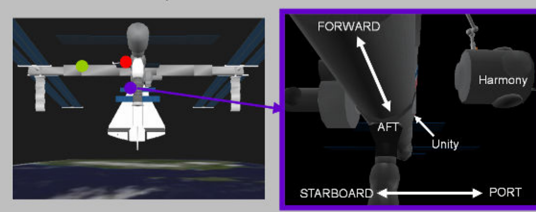
Lesson One

- When the Shuttle first arrived at the ISS during STS-120, the crew needed to move the new Harmony module from the Shuttle to the port side of the Unity module.
- As the secondary operator, you will have the three camera views shown successively below:



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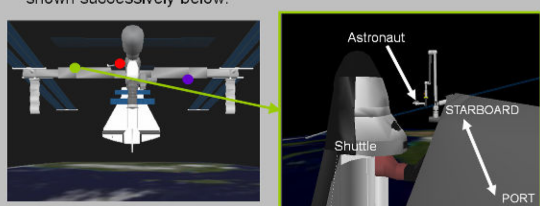
Lesson Two

- Crewmembers performed EVAs to set up the new module and move a solar array, then they moved back to the airlock on the starboard side of the core modules.
- As the secondary operator, you will have the three camera views shown successively below:



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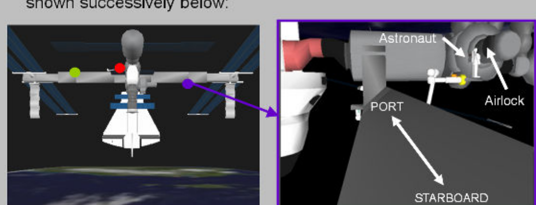

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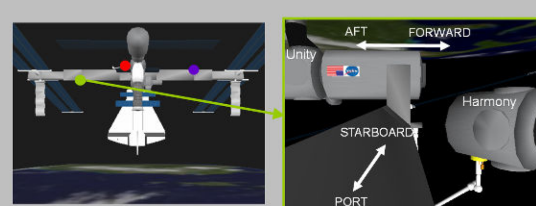
Lessons Three & Four

- After the Shuttle left, the ISS crew had to move the Harmony module from the port side of Unity to the forward end of the Core Modules.
- As the secondary operator, you will have the three camera views shown successively below:



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Lessons Three & Four

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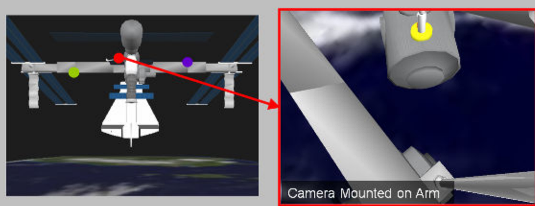
- As the secondary operator, you will have the three camera views shown successively below:



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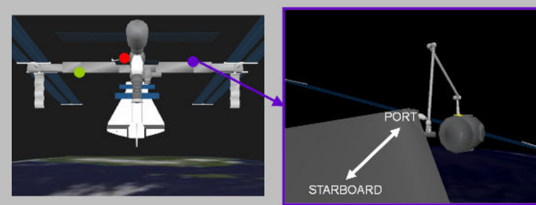
Lessons Three & Four

- After the Shuttle left, the ISS crew had to move the Harmony module from the port side of Unity to the forward end of the Core Modules.
- As the secondary operator, you will have the three camera views shown successively below:



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Lesson Overviews

- During robotic operations, the primary operator tells the secondary operator what the arm is about to do.
- You will hear a "invisible" primary operator telling you what they are doing with the arm.
  - Examples:
    - "I am moving the arm upwards to get above the truss."
    - "Now I will move the arm forward over the truss."

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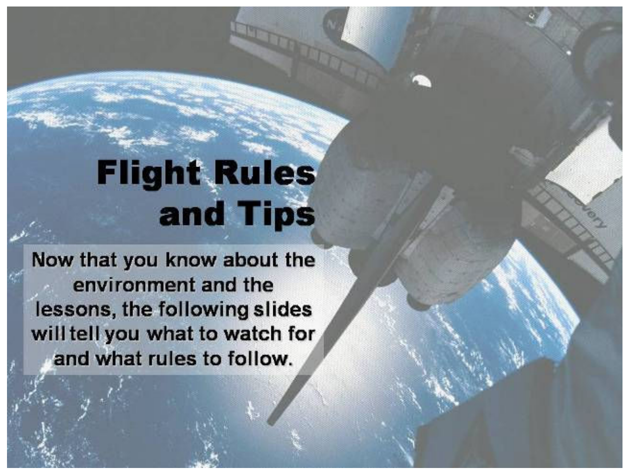
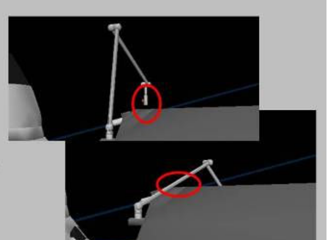
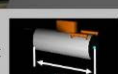


Problems to Watch For

- During each activity, watch for three types of problems:
  - Clearance Violations
    - Stop the arm if any part of it or its payload gets within 0.6 m of the truss, the Core modules, or the Shuttle
    - You WILL NOT see warnings on the screen



Remember:



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Problems to Watch For

- Singularities
  - Stop the arm if the elbow or wrist yaw joint are about to hit a singularity.

- Unexpected Motions
  - Stop the arm whenever its movement doesn't follow the primary operator's plan.

"Now I will move aft over the truss."

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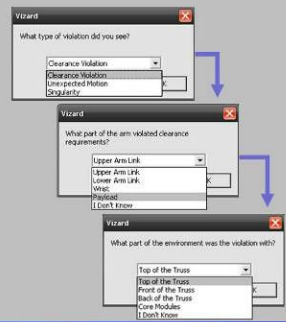
Problems to Watch For

- There will only be at most one problem per activity. Some activities will not have any problems.
- Press SPACEBAR to stop the arm when you see a problem occur. On the right is an example of the messages you will see.
- The next activity will begin when you have answered the questions.



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Strategies

- Use all of the available camera views. You may not need them all at once but keep checking.
- As the arm moves, look for what is near it and what the joints are doing.
- Make sure you listen to the primary operator's plans. Consider what the arm will do and where it will be if the plan is carried out.

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Rewards and Penalties

- Failing to detect problems during robotic operations in space could damage hardware or endanger the crew's lives.
- Your payment will be affected by how quickly and accurately you can identify problems.
- If your final score is positive, you will receive a bonus
  - If you correctly identify all the problems, you will receive an additional $12.00.
  - If your score is negative, you will not lose any money
- For the last lesson, the penalty for false alarms will increase.

	Problem	No Problem
Arm Stopped	Good Detection + $0.50	False Alarm -$0.25
Arm Not Stopped	No Detection -$0.50	$0.00

	Problem	No Problem
Arm Stopped	Good Detection + $0.50	False Alarm -$0.50
Arm Not Stopped	No Detection -$0.50	$0.00

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-OR-

Rewards and Penalties

- Failing to detect problems during robotic operations in space could damage hardware or endanger the crew's lives.
- Your payment will be affected by how quickly and accurately you can identify problems.
- If your final score is positive, you will receive a bonus:
  - If you correctly identify all the problems, you will receive an additional $12.00.
  - If your score is negative, you will not lose any money

	Problem	No Problem
Arm Stopped	Good Detection + $0.50	False Alarm -$0.25
Arm Not Stopped	No Detection -$0.50	$0.00

Version 3.5 Summer 2008
MVL Space Teleoperation Experiment

APPENDIX O - Experiment 2 Post-Test Questionnaire 2

Congratulations, you've finished the experiment! Please answer the following questions about your experiences and, if you wish, add any comments.

1. If you experienced any of the following, please circle your level of discomfort:

EFFECT	NONE				SEVERE
A. Nausea	1	2	3	4	5
B. Dizziness	1	2	3	4	5
C. Disorientation	1	2	3	4	5
D. Eyestrain	1	2	3	4	5
E. Blurred vision	1	2	3	4	5
F. Sweating	1	2	3	4	5
G. Headache	1	2	3	4	5
H. General discomfort	1	2	3	4	5
I. Mental fatigue	1	2	3	4	5
J. Other __________	1	2	3	4	5

2. How enjoyable/interesting was your interaction with the virtual environment?

Boring 1 2 3 4 5 Captivating

Comments?

3. Rate your proficiency on the following items, after going through the Power Point training:

	LOW				EXPERT
- Understanding your objective	1	2	3	4	5
- Understanding the problems to watch for	1	2	3	4	5
- Understanding the environment	1	2	3	4	5
- Understanding the camera views	1	2	3	4	5

4. To observe the task, you:
   - O Spent about equal amounts of time looking at each of the three displays
   - O Spent most of your time looking at two of the three displays
   - O Spent most of your time looking at one of the displays
   - O Other: ____

5. Was one of the problems harder for you to notice than others?
   - O Clearance Violations (why? ____)
   - O Unexpected Motions (why? ____)
   - O Singularities (why? ____)
   - O All three were of equal difficulty

6. Was it more difficult to observe problems during a specific task type?
   - O The first task type was the hardest (moving the module with the Shuttle there)
   - O The second task type was the hardest (moving the astronaut)
   - O The third task type was the hardest (moving the module without the Shuttle there)
   - O All three were of equal difficulty

If you thought one was harder than the others, why?

7. Did you try to memorize the layout of the environment during your orientation, or wait and learn it as you went through the tasks?
   - O I spent a lot of time exploring the environment during the orientation to figure things out
   - O I decided to just figure out how things were laid out as I did the tasks
   - O Other: ____

8. Did the upside-down cameras make observing significantly more difficult for you?
   - O No, I had no problem with the upside-down cameras.
   - O It was a little more difficult in the beginning, but I got used to it pretty quickly.
   - O The cameras made observing more difficult throughout the experiment.

9. How did you react when the penalty for false alarms changed for the last lesson?
   - O I was much more careful about making a false alarm and therefore may have missed some problems
   - O I was pretty confident in my abilities and didn't do anything differently from the previous lesson
   - O I forgot that the penalty had changed
   - O The bonus payment meant nothing to me; I didn't do anything differently
   - O Other: ____

10. Do you have additional suggestions/comments regarding this part of the experiment?

Thank you! Please return this questionnaire to the experimenter.

APPENDIX P - Experiment 2 Post-Test Questionnaire 2 Results[34]

Subj	Q2	Q3 A	Q3 B	Q3 C	Q3 D	Q4	Q5	Q6	Q7	Q8	Q9
302[35]	3	5	3	4	3	2	2	3	1	2	
303[35]	5	5	5	5	5	1	0	3	0	1	
304[35]	4	4	3	4	3	2	0	3	1	0	
401	4	4	4	2	3	2	6	0	1	1	N/A
415	4	5	4	4	3	1	0	3	0	1	N/A
408	3	4	4	3	2	1	2	3	1	2	1
410	4	4	5	4	4	1	0	3	0	0	N/A
432	4	4	3	3	5	1	0	0	1	2	N/A
440	4	5	4	5	4	1	2	3	1	1	N/A
439	1	3	3	2	2	1	0	2	1	1	N/A
433	2	5	5	3	4	1	2	3	1	1	3
441	3	4	4	4	4	1	2	0	1	1	3
421	4	4	4	4	3	1	0	2	1	0	1
417	3	4	4	4	3	1	0	3	5	1	N/A
442	4	4	4	4	4	1	0	3	1	1	N/A
436	4	4	3	3	3	0	3	3	2	0	0
403	3	4	4	2	2	1	0	0	1	2	3
434	4	5	4	4	4	1	2	3	1	0	N/A

[34] Answer Coding

For questions 2-5, the value in the table corresponds to the answer marked

For questions 6-9, the value in the table corresponds to the answers as follows:

0 = first answer option
1 = second answer option
2 = third answer option
3 = fourth answer option
4 = first, second, and fourth answer options
5 = first and second answer options

[35] These subjects participated in the pilot study; a question about their behavior after the pay change was not included in the questionnaire. Subject 301 was not given post-test questionnaires.

APPENDIX Q - Experiment 2 Trial Design Summary

Primary Operator

Trial	Cameras[36]	Target Point Location/Orientation
1	2, EEF, 3	Above forward/port corner of table, pitch down 45°
2	1, EEF, 4	Above red berth on floor, roll left 30°
3	2, EEF, 3	Above middle of table, pitch down 60°
4	1, EEF, 4	Above forward/port corner of table, pitch down 45°
5	2, EEF, 3	Above red berth on floor, roll left 30°
6	1, EEF, 4	Above middle of table, pitch down 60°

Secondary Operator

Lesson	Trial	Problem to Detect
1	1	Clearance Violation
1	2	Singularity
1	3	Unexpected Motion
1	4	No Problem
1	5	Unexpected Motion
1	6	Singularity
1	7	No Problem
1	8	Clearance Violation

Lesson	Trial	Problem to Detect
2	1	Unexpected Motion
2	2	No Problem
2	3	Singularity
2	4	Clearance Violation
2	5	Singularity
2	6	No Problem
2	7	Unexpected Motion
2	8	Clearance Violation

[36] Cameras 1 and 4 were the "low disparity" cameras; cameras 2 and 3 were the "high disparity" cameras.

Lesson	Trial	Problem to Detect
3	1	Clearance Violation
3	2	No Problem
3	3	Singularity
3	4	Unexpected Motion
3	5	No Problem
3	6	Unexpected Motion
3	7	Clearance Violation
3	8	Singularity

Lesson	Trial	Problem to Detect
4	1	Singularity
4	2	Unexpected Motion
4	3	No Problem
4	4	Clearance Violation
4	5	Singularity
4	6	Clearance Violation
4	7	No Problem
4	8	Unexpected Motion

APPENDIX R - Experiment 3 Subject Basic Data

Subj	Gender	Writing Hand	MRT	PTA	PSVT
1	M	Right	20	19.2	20
2	M	Right	28	17.8	22
3	M	Right	18	21.9	18
4	M	Right	28	20.5	28

APPENDIX S - Experiment 3 Pre-Test Questionnaire

Gender: F M **Age**: _____

Writing Hand: Right Left **Major/Course #**: __________

Colorblind? Y N (If yes, can you differentiate between red and green? ________________________)

1. **Do you have experience with Virtual environments (e.g. 3-D games, CAD, graphic design, etc.)?**
(Yes No) (If "Yes," can you please describe this experience?)

2. **Do you have experience with joysticks/game controllers? (e.g. computer/video games, robotics)**
(Yes No) (If "Yes," can you please describe this experience?)

3. **How many hours per day do you use the computer?**
☐ 0 ☐ 1 – 3 ☐ 3 – 5 ☐ 5 – 7 ☐ More than 7

4. **What do you typically use the computer for? (Please check all that apply)**
☐ Email/Internet/Word processing ☐ Design (Graphical/Mechanical)
☐ Programming ☐ Gaming ☐ Other________________________________

5. **Have you previously or do you currently have a habit of playing video/computer games?**
(Yes No) (If "No," go to question 10)

6. **How old were you when you started playing video/computer games?**
☐ < 5 ☐ 5 – 12 ☐ 12 – 18 ☐ 18- 25 ☐ > 25

7. **On average, how often (hours/week) did you play video/ computer games <u>when you played the most frequently</u>?**
☐ 1 – 3 ☐ 3 – 7 ☐ 7 –14 ☐ 14 – 28 ☐ > 28

How many years ago was that?
☐ 0 ☐ 3 – 5 ☐ 5 – 10 ☐ 10 – 15 ☐ > 15

8. **On average, how often (hours/week) have you played video/computer games <u>in the past 3 years</u>?**
☐ 0 ☐ 1 – 3 ☐ 3 – 7 ☐ 7 –14 ☐ 14 – 28 ☐ > 28

9. **What kind of video/computer games do you play the most? (check as many as apply)**
☐ First person ☐ Role-playing/Strategy ☐ Arcade/Fighting
☐ Simulation (driving, flying) ☐ Sports ☐ Other __________________

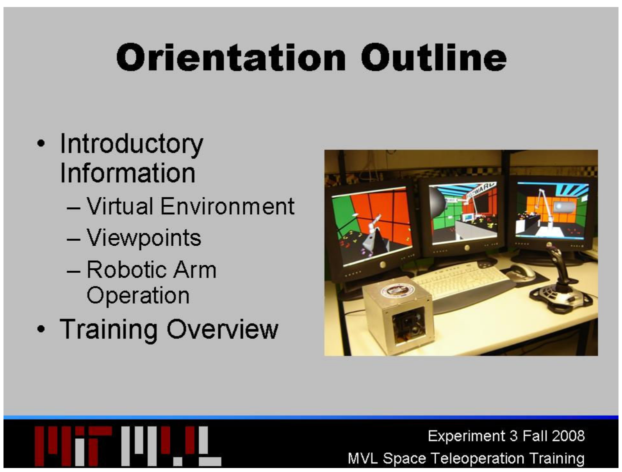
12. **Have you ever taken any spatial ability tests before?**
☐ Yes, for a previous robotics experiment with the MVL
☐ Yes, for some other reason (please list: ____
____)
☐ No

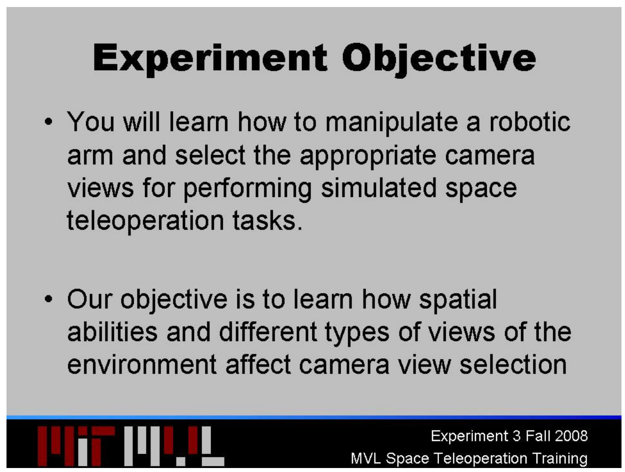
Thank you. Please give this questionnaire back to the experimenter.

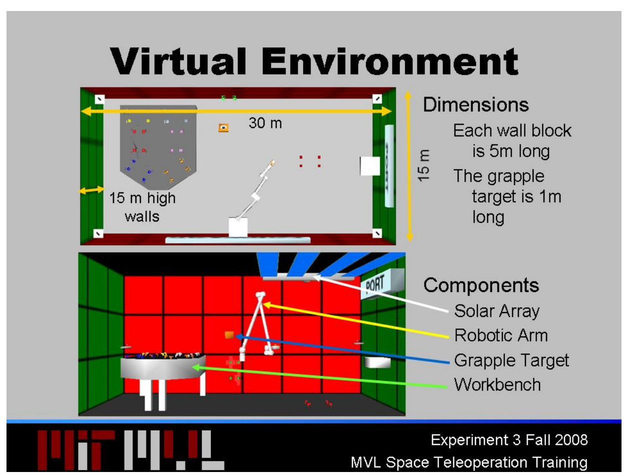
APPENDIX T - Experiment 3 Pre-Test Questionnaire Results

	501	502	503	504
3-D Exp?	Yes	Yes	Yes	Yes
3-D Type	CAD	N/A	Games, CAD	Games
Contr Exp?	No	Yes	Yes	Yes
Contr Type	N/A	N/A	Comp/Video	Comp/Video & Robotics
Comp Hrs	5-7	7 +	7 +	5-7
Comp Use	E & P & D	E & P	E & P & G	E & G
Game Habit	No	Yes	Yes	Yes
Game Age	N/A	5-12	5-12	5-12
Game Hrs	N/A	> 28	14-28	> 28
Game Yrs	N/A	3-5	5-10	5-10
Game Recent	N/A	3-7	1-3	7-14
Game Type	N/A	R	R & Sp	R
Previous SA	No	No	No	Yes, AFOQT

APPENDIX U - Experiment 3 Training

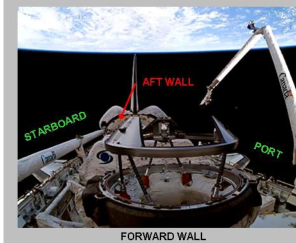


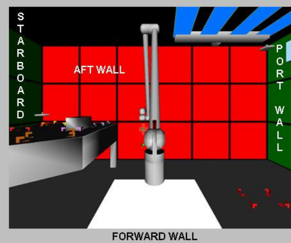




Virtual Environment

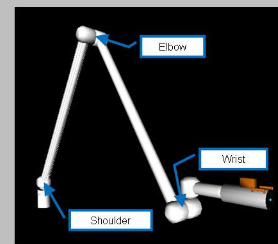
The environment was modeled after a NASA training tool for astronauts. The walls are named "forward", "port", "starboard" and "aft" as though the environment were a space shuttle's payload bay.

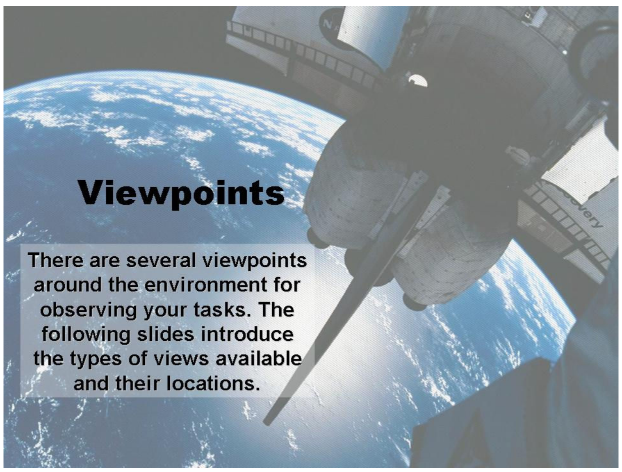




Virtual Environment

- Robotic Arm
  - Like a human arm, the robotic arm has three elements: a shoulder, an elbow, and a wrist.
  - It is 14 m long when fully extended.
  - The arm simulates the one used by astronauts onboard the space shuttle and the space station.



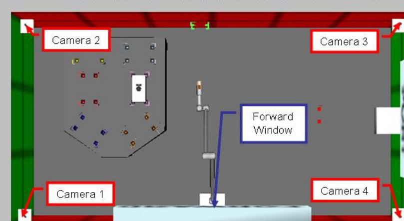


Viewpoints

There are several viewpoints around the environment for observing your tasks. The following slides introduce the types of views available and their locations.

Viewpoints

- You will have three monitors giving you views of the environment.
- There are 5 possible views:
  - Four views from numbered cameras inside the room
  - One view from the window on the Forward wall



You will be presented with several target scenarios and must correctly select the best camera views.

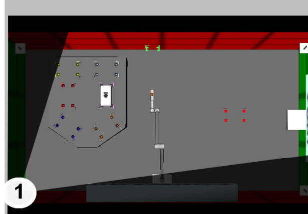
More details on your task will be given in a few slides.

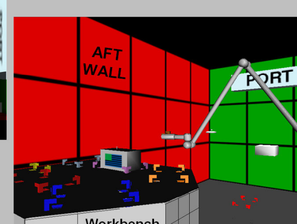
Viewpoints

The following slides show each of the viewpoints from the numbered cameras.

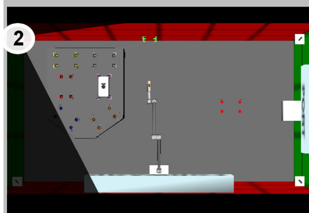
The viewpoints will be shown on the right. On the left, you can see where the camera is located.

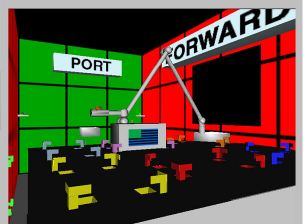
Viewpoints





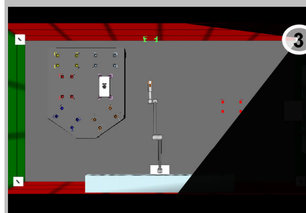
Viewpoints



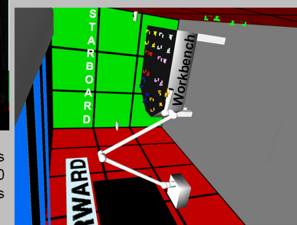


Experiment 3 Fall 2008
MVL Space Teleoperation Training

Viewpoints



Camera 3 is rotated 90 degrees



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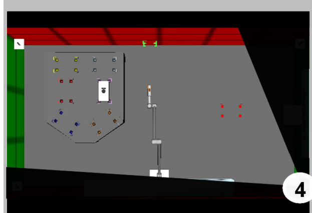
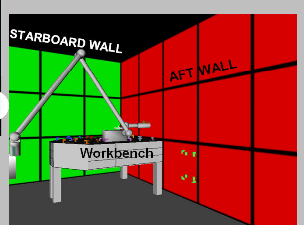
Viewpoints





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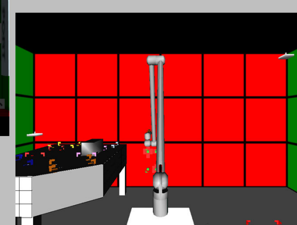
Viewpoints



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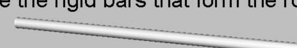
Robotic Arm Operation

The following slides introduce how the arm works and how to operate the hand controller.

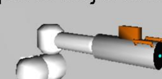
Robotics Terminology

- **Links** are the rigid bars that form the robotic arm.



- **Joints** allow two links to rotate with respect to one another.

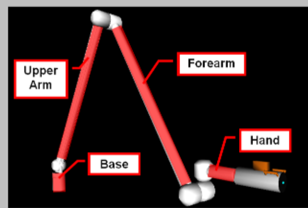
- The **End-Effector** is the 'grasping finger' of the arm, made up of multiple small joints and links.



Experiment 3 Fall 2008
MVL Space Teleoperation Training

Robotics Terminology

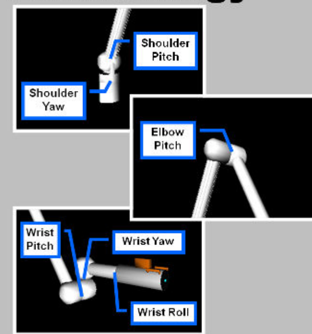
- The arm has:
  - 4 Links



Experiment 2.1 Summer 2008
MVL Space Teleoperation Training

Robotics Terminology

- The arm has:
  - 4 Links
  - 6 Joints
    - The arm's joints allow it to move 6 ways in 3-D space
      - Left/right
      - Up/down
      - Forward/backward
      - Pitch
      - Yaw
      - Roll



Version 2.0 Winter 2008
MVL Space Teleoperation Experiment

Translational Hand Controller

The translational hand controller allows the arm to move left/right, up/down, and forward/backward.

It does not move the arm's individual joints, it just changes the position of the end-effector tip.

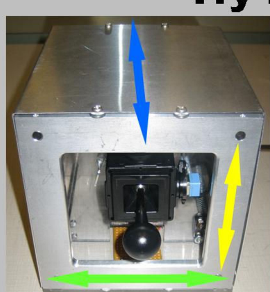
Experiment 3 Fall 2008
MVL Space Teleoperation Training

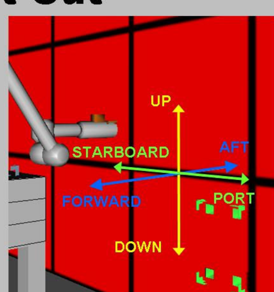
Try It Out

- The following slides will give you a chance to practice manipulating the arm.
- The other two monitors will show you views of the environment
  - The first monitor shows the view from Camera 2
  - The second monitor shows the view from Camera 4
- Follow the instructions on the slides to test different things with the arm. You will be given a chance to practice more with some sample tasks in a few minutes.

Experiment 3 Fall 2008
MVL Space Teleoperation Training

Try It Out





Move the controller left/right

- Notice that the yaw joints work together to keep end-effector pointing in the same direction

Experiment 3 Fall 2008
MVL Space Teleoperation Training

Training Overview

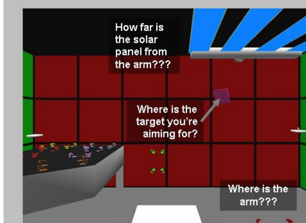
- Learning how to properly select camera views is a big part of the astronauts' robotics training.
- For every task, three types of views are needed:

Training Overview

Big Picture View

Shows as much of the entire task as possible with a single view.

BAD CHOICE	GOOD CHOICE
All you can see is the target	You see multiple important items/have situational awareness of environment

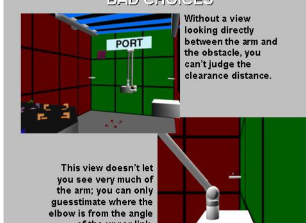


Training Overview

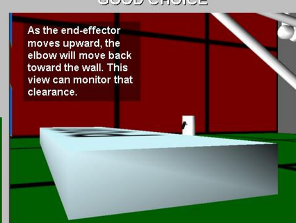
Clearance View

- Used for determination of the distance between the arm and an obstacle
- You must first determine the most likely clearance obstacle for the scenario
  - **End-Effector** or **Elbow** clearance (the following example deals with elbow clearance)

BAD CHOICES



GOOD CHOICE

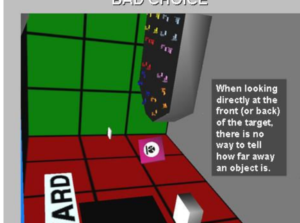


Training Overview

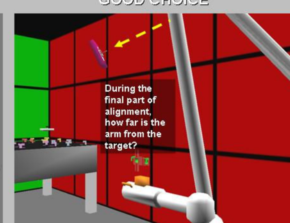
Task View

- Used for determination of the arm's distance from target during alignment
- This view should be orthogonal to the top surface of the target.

BAD CHOICE



GOOD CHOICE



Training Overview

- Use the keyboard to select the cameras
  - Pick a monitor to modify
    - F5 = Big Picture (left monitor)
    - F6 = Clearance (center monitor)
    - F7 = Task (right monitor)
  - Pick a camera for that monitor
    - 1,2,3,4 = Corner Cameras
    - 5 = Window
  - Once a camera has been selected, use ← and → to pan to the left and right (the window cannot be panned)

You will be given a "cheat sheet" with the key commands

Try It Out

- Task 1: Press 'SPACEBAR' to make a practice target appear in the environment.
  - Follow the directions that appear on the screen
  - Use the hand controller to make the arm touch the target
- Task 2: Follow the directions that appear on the screen to practice selecting camera views
  - Use the keyboard to pick the **Clearance** and **Task** views for the scenario shown to the right.
  - Press 'SPACEBAR' when you're finished.

Complete the Practice Tasks before Continuing to the Next Slide

Training Overview

- You will complete 3 lessons, and each is made up of 4 trials
  - Step 1: Study the paper maps and click OK only when you are ready to select big picture, clearance, and task views.
  - Step 2: Follow the instructions on the screen to select initial big picture, clearance, and task cameras. Use the information provided by the paper maps to choose the best views.
  - Step 3: Check your initial selections and make changes as necessary in order to get the best set of views possible.
  - Step 4: Press 'SPACEBAR' to lock in your selections. You will be asked what potential clearance problem you were concerned with before the next trial begins.

Experiment 3 Fall 2008
MVL Space Teleoperation Training

Training Overview

- With some scenarios, there may be multiple cameras that all meet the criteria for a view type. Select the one that you feel is best.
- Try not to have important objects (the target, the wall the arm may collide with, etc.) on the very edge of a view. You want to be able to see them as clearly as possible.
- You cannot use any single camera for more than one of the required view types.
- Remember that you are choosing the best cameras for the entire duration of the task, not just for the initial state of the arm

Experiment 3 Fall 2008
MVL Space Teleoperation Training

Training Overview

- There is no time limit for each task, but you are being timed, so work as quickly and accurately as possible.
- After finishing all of the tasks, you will receive a performance rating based on your speed and number of correct selections.

<u>Performance Ratings</u>

1. Corps Applicant (worst)
2. Astronaut Candidate
3. Mission Specialist
4. Flight Engineer
5. Lead Arm Operator (best)

Experiment 3 Fall 2008
MVL Space Teleoperation Training

APPENDIX V - Experiment 3 Post-Test Questionnaire

Congratulations, you have completed the experiment! We'd like to get some information about your training; please answer each question and, if you wish, add any comments.

1. If you experienced any of the following, please circle your level of discomfort:
2.

	EFFECT	NONE				SEVERE
A.	Nausea	1	2	3	4	5
B.	Dizziness	1	2	3	4	5
C.	Disorientation	1	2	3	4	5
D.	Eyestrain	1	2	3	4	5
E.	Blurred vision	1	2	3	4	5
F.	Sweating	1	2	3	4	5
G.	Headache	1	2	3	4	5
H.	General discomfort	1	2	3	4	5
I.	Mental fatigue	1	2	3	4	5
J.	Other _____________	1	2	3	4	5

2. How enjoyable/interesting was your interaction with the virtual environment?

Boring 1 2 3 4 5 Captivating

Comments?

3. Rate your proficiency on the following items, after going through the Power Point training:

	LOW				EXPERT
- Understanding the Viewpoint types	1	2	3	4	5
- Understanding the Cameras	1	2	3	4	5
- Understanding the Task	1	2	3	4	5

4. Was one of the viewpoint types more difficult than the others?
   - O Selecting the Clearance View was the hardest
   - O Selecting the Task View was the hardest
   - O Selecting the Big Picture View was the hardest
   - O Selecting the views were equally difficult

5. Did you try to memorize the layout of the environment during your orientation, or wait and learn it as you went through the tasks?
   - O I spent a lot of time studying the pictures of the environment to figure things out
   - O I decided to just figure out where things were as I was working with the arm
   - O Other: ____

6. Do you have additional suggestions/comments regarding the experiment?

Thank you! Please return this questionnaire to the experimenter.

APPENDIX W - Experiment 3 Post-Test Questionnaire Results

	501	502	503	504
Q2	5	5	4	4
Q3A	4	4	3	5
Q3B	4	4	4	4
Q3C	3	4	3	4
Q4	0	1	3	2
Q5	1	1	0	0

APPENDIX X - Description of Codes[37]

EXPERIMENT 1

- Familiarization.py
    - Co-requisite program for the PowerPoint orientation (Appendix D). Ran on two screens only and consisted of the MVL DST environment and arm. Allowed subjects to practice moving the arm and determine what happens when problems (singularities and hard stops) are reached.
    - Did not record any performance data
- MVL-DST-v.5.5.py
    - Main data-taking program for the experiment. Was used for all four lessons; the experimenter inputted the lesson number at startup so that the program would import the correct files.
    - Recorded Summary Data Files, Session Data Files, Movement Files, End Data Files, and Joint Angle Files for each lesson.
- bimanual_control.py
    - Bimanual Control (BMC) Test. Subjects maneuvered the arm in internal control mode to trace the crosshairs around the edge of an oval. They were scored on their ability to quickly and accurately perform the task.
    - Recorded a Summary Data file with the following variables for each repetition: total time, time spent moving, time spent moving along 2 or more axes, time spent both rotating and translating, number of changes in direction, number of multi-axial changes in direction, number of bimanual changes in direction, average distance error from the edge of the oval, and average angle error from being tangent to the oval.

EXPERIMENT 2 – Primary Operator

- Familiarization.py
    - Co-requisite program for the PowerPoint orientation (Appendix J). Ran on two screens only and consisted of the MVL DST environment and arm. Allowed subjects to practice moving the arm and determine what happens when problems (singularities and hard stops) are reached.
    - Did not record any performance data
- MVL-DST-v.5.6.py
    - Main data-taking program for the primary operator portion of the experiment.
    - Ran in one of two modes: practice or training. Subjects used the single trial in practice mode to test their understanding of the task. Data was collected during the 6 training mode trials.
    - Recorded Summary Data Files, Session Data Files, Movement Files, End Data Files, and Joint Angle Files.
- bimanual_control.py

[37] Codes are available from the MIT Man-Vehicle Laboratory upon request.

EXPERIMENT 2 – Secondary Operator

- Familiarization_ISS_P.py, Familiarization_ISS_1.py, Familiarization_ISS_2.py, and Familiarization_ISS_3.py
  - Programs used to create the recordings that the subjects viewed during the secondary operator lessons. Consisted of the MVL ISS environment and arm. Only capable of running and saving one trajectory per startup.
  - One program per lesson setup: P = practice; 1,2,3 correspond to lesson numbers (setup is the same for lessons 3 and 4)
  - Recorded Joint Angle Data files
- ISS_flyaround.py
  - Co-requisite program for the PowerPoint orientation (Appendix M). Ran on two screens only and consisted of the MVL ISS environment and arm (though the arm was stationary). Subjects controlled a free-flying camera to study the layout of the environment.
  - Did not record any performance data
- playback_ISS_P.py, playback_ISS_1.py, playback_ISS_2.py, playback_ISS_3.py, and playback_ISS_4.py
  - Main data-taking program for the secondary operator portion of the experiment.
  - One program per lesson setup. The joint angle data files created by the familiarization_ISS programs were read in and used to show a recording of the arm moving.
  - Recorded Summary Data Files.

EXPERIMENT 3 – Pilot Study

- Familiarization.py
  - Co-requisite program for the PowerPoint orientation (Appendix S). Ran on two screens only and consisted of the MVL DST environment and arm. Allowed subjects to practice moving the arm, determine (with hands-on interaction) the purpose of clearance and task views, and practice setting up cameras for a trial.
  - Did not record any performance data
- MVL-DST-v.6.10.py
  - Main data-taking program for the experiment. Was used for all three lessons; the experimenter inputted the lesson number at startup so that the program would import the correct files.
  - Recorded Summary Data Files for each lesson.